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AL-CP-89-01 AD:

PROCEEDINGS OF THE 10 MAY 1989 ANTIPROTON TECHNOLOGY WORKSHOP

A compilation of presentation materials from the workshop held at Brookhaven National Laboratory, jointly sponsored in accordance with the AL/DoE Memorandum of Agreement for Applied Research in Energy Storage support from Brookhaven National Laboratory

May 1989

Editor: Gerald D. Nordley

Approved for Public Release

Astronautics Laboratory (AFSC)

Air Force Space Technology Center
Space Division, Air Force Systems Command
Edwards Air Force Base,
California 93523-5000

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FOREWORD

This special report comprises the presentations provided by speakers at the Antiproton Technology Workshop held at Brookhaven National Laboratory (BNL) 10 may 1989 jointly sponsored under the Astronautics Laboratory (AFSC) / Department of Energy-BNL Memorandum of Agreement for support of Applied Research In Energy Storage (ARIES). This special report has been reviewed and approved in accordance with the distribution statement on the cover an on the DD form 1473.

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Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release. Distribution is unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AL-CP-89-001	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Astronautics Laboratory 6b. OFFICE SYMBOL *(If applicable)* LSX	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS *(City, State, and ZIP Code)* Edwards Air Force Base, CA 93523-5000	7b. ADDRESS *(City, State, and ZIP Code)*
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL *(If applicable)*	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS *(City, State, and ZIP Code)*	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.
62302F	5730	00	5E

11. TITLE *(Include Security Classification)*
(U) PROCEEDINGS OF THE 10 MAY 1989 ANTIPROTON TECHNOLOGY WORKSHOP

12. PERSONAL AUTHOR(S)
Nordley, Gerald D., Editor

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
Special	FROM 89/5/10 TO 89/5/10	89/05	

16. SUPPLEMENTARY NOTATION
A compilation of presentation materials from the workshop held at Brookhaven National Laboratory, jointly sponsored IAW AL/DoE Memorandum of Agreement for Applied Research in Energy

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP
20	07	
20	08	

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Antiproton Beams, Imaging, NDA/NDE, Radiotherapy, Condensed Antimatter, CP Violation

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

This workshop, held at Brookhaven National Laboratory, 10 May 1989, was a follow-on to the Antiproton Science and Technology Workshops held at the RAND Corporation in Santa Monica through October 1987 following the Air Force Project Forecast II initiative in Antiproton Technology. The workshop was attended by about 50 researchers from a wide variety of disciplines, including medicine, particle physics, and the aerospace industry. New, more efficient technology for a variety of scientific, medical, and industrial uses could result from antiproton experiments proposed by workshop participants. Antiprotons are particles of antimatter which release highly penetrating radiation when they are stopped in normal matter. According to presentations at the Antiproton Technology Workshop this radiation can be used, in very small quantities, to image objects and determine their composition and density. In larger amounts, the radiation could be used to kill cancer tumors or produce highly localized heating and shock waves. DOE plans are contingent on potential user support.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Gerald D. Nordley, Maj, USAF	22b. TELEPHONE *(Include Area Code)* (805) 275-5653	22c. OFFICE SYMBOL LSX

DD Form 1473, JUN 86 *Previous editions are obsolete.* SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

Block 16.

Storage support from Brookhaven National Laboratory.

Accession For

A-1

PROCEEDINGS OF THE ANTIPROTON TECHNOLOGY WORKSHOP*

HELD AT BROOKHAVEN NATIONAL LABORATORY 10 MAY 1989

EXECUTIVE SUMMARY

1. Background

New, more efficient technology for a variety of scientific, medical, and industrial uses could result from antiproton experiments proposed by a workshop of government, industry and academic researchers at Brookhaven National Laboratory, Wednesday 10 May 1989. Antiprotons are particles of antimatter which release highly penetrating radiation when they are stopped in normal matter. According to presentations at the Antiproton Technology Workshop this radiation can be used, in very small quantities, to image objects and determine their composition and density. In larger amounts, the radiation could be used to kill cancer tumors or produce highly localized heating and shock waves. The Alternate Gradient Synchrotron, or "AGS", located at Brookhaven is one of the few particle accelerators in the world capable of making the number of antiprotons needed to perform the experiments.

The workshop was a follow-on to the Antiproton Science and Technology Workshops held at the RAND Corporation in Santa Monica through October 1987 following the Air Force Project Forecast II initiative in Antiproton Technology. The workshop was attended by about 50 researchers from a wide variety of disciplines, including medicine, particle physics, and the aerospace industry.

2. Workshop Results

Aerospace uses include the detection of physical or chemical flaws in the manufacture of composite materials, with implications for increased aviation safety and lighter, less expensive rockets.

An existing market of about $100 billion a year in medical imaging and radiotherapy has attracted the interest of private investors. Demonstrations of rapid, low radiation imaging of hard tissues and killing cancer tumors might prove the viability of a new, privately funded accelerator to provide antiprotons for medical and industrial uses.

Atomic chemists want to make antihydrogen to see if it obeys the same physical rules as ordinary hydrogen. Antihydrogen would be made by combining antiprotons with the anti-electron, or positron, the first form of antimatter discovered back in 1935.

Physical scientists are interested in radiation effects and small but intense shock waves that could be produced by pulsed antiproton beams. Protection of spacecraft from solar storms and meteor impacts are among many uses of radiation and shock data.

Particle physicists are interested in broken symmetries in particle reactions which one might expect to have identical outcomes, but don't. Such reactions help tell us how the universe was made and what its ultimate destiny might be.

Antiproton Workshop members came from organizations as diverse as the Lahey Clinic in Boston, the Astronautics Laboratory at Edwards Air Force Base, General Dynamics Corporation in Fort Worth, and the University of Illinois. The workshop agenda is provided as table 1. Workshop attendance is provided as table 2.

The only source of antiprotons suitable for many of the experiments discussed is the European accelerator in Switzerland, which has long waiting lines for experimenters. The researchers generally agreed that an antiproton source in the United States, perhaps based on the Brookhaven AGS accelerator, Fermilab's accelerator, or the booster ring planned for the Superconducting Supercollider will make United States science and technology significantly more competitive in areas discussed. Significant informational activities concerning antiproton technology continue within DOE. Potential user interest expressed as serious proposals is a significant determinant of DOE support.

*The workshop was jointly sponsored by the Astronautics Laboratory and Brookhaven National Laboratory (DOE).

Table 1. Antiproton Technology Working Group Final Agenda

0830	Informal discussions		
0900	Welcome and Administrative Remarks	*Dr S. Baron, BNL; Maj G. Nordley, AL*	
0915	IMAGING AND ANALYSIS - T. KALOGEROPOLOUS, SYRACUSE		
0915	Stopping Power of MeV Proton and Antiproton Beams	R. A. Lewis	The Pennsylvania State U.
0930	*Recent Simulation Results of ASTER*	Robert Muratore	Syracuse University
0945	Pbar Testing of Hydrogen Effects in Sealed Carbon-Carbon Composites	Harris Carter	Gen Dynamics Ft Worth
1000	Potential for Antiprotons in Radiation Oncology	M. Leibenhaut, MD	Lahey Clinic Medical Cen.
1015	Prospects for a Commercial Antiproton Source	*Brian Von Herzen*	*Antimatter Technology Corp*
1030	Break		
1045	ANTIHYDROGEN AND CONDENSED MATTER PHYSICS - CHRIS BRASIER, U. DAYTON (AL)		
1045	*Prospects for Exciting Extreme* States in Nuclear Matter with Intense Antiproton Beams	E. D. Minor	The Pennsylvania State U.
1100	Status of AL Studies Relating to Condensed Antimatter	Gerald Nordley	Astronautics Lab (AFSC)
1115	Electromagnetic Traps for Atomic Antihydrogen	Isaac Silvera	Harvard University
1130	Antihydrogen Production	Arthur Rich	University of Michigan
1200	LUNCH: BNL CAFETERIA		
1215	Luncheon Speech: HQ DoE Antiproton Activities	David Goodwin	Dept of Energy
1300	OPTION: AGS TOUR OR INFORMAL DISCUSSIONS		
1400	ENERGY DEPOSITION AND RELEASE - GERALD SMITH, PENN STATE		
1400	Antiproton Catalyzed Fusion	T. Kalogeropolous	Syracuse University
1415	Antiproton Induced Fusion Reaction	W. S. Toothacker	The Pennsylvania State U.
1430	Options for a Laboratory Microfusion Facility (LMF)	Bruno Augenstein	The RAND Corporation
1445	Modeling Antiproton - Plasma Interactions	John Callas	Jet Propulsion Laboratory
1500	Concepts for Experimental Determination of Radiation Shielding and Metal Clad Pellet Performance	Brice Cassenti	UTRC - Hartford
1515	Break		
1530	PARTICLE PHYSICS - D. C. PEASLEE UNIVERSITY OF MARYLAND		
1530	Introduction to CP Violation Studies with Pbars	D. C. Peaslee	University of Maryland
1545	Test of CP Non-conservation in Pbar-P to Ξbar- Ξ	A. M. Nathan	University of Illinois
1600	Studies of CP Violation with Pure K_0 K_0bar Beams from Pbars	James Miller	Boston University
1615	Search for CP Violation in Pbar-P to J/Ψ	Gerald A. Smith	The Pennsylvania State U.
1630	Studies of Rare Modes of Pbar-P Annihilation	C. B. Dover	Brookhaven N.L.
1645	Antiproton Production Calculation by the Multistring Model VENUS Computer Code	H. Takahashi	Brookhaven N. L.
1700	Closing Remarks	G. Nordley	AL (AFSC)

Table 2. Attendees at the Antiproton Technology Workshop

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CONTENTS

* Copies of viewgraphs were unavailable at the time of compilation (17 May 1989). They may be inserted if recieved later.

STOPPING POWER OF MeV PROTON AND ANTIPROTON BEAMS

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LABORATORY FOR ELEMENTARY PARTICLE SCIENCE
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Note: We regret that copies of the transparencies used in Dr Lewis' excellent presentation were not available for inclusicıı in the proceedings.

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

RECENT SIMULATION RESULTS OF ASTER

ROBERT MURATORE

DEPARTMENT OF PHYSICS
SYRACUSE UNIVERSITY

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

Recent Simulation Results of ASTER

Robert Muratore
Syracuse University

Recent Simulation Results of ASTER

Robert Muratore

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201 Physics Building, Syracuse, New York 13244-1130 USA

Abstract. ASTER, an imaging technique proposed several years ago, is now ready to be built. ASTER uses antiprotons to form direct three dimensional images of the target density profile. Useful images can be obtained with less than one million antiprotons, well within current production levels. ASTER has potential advantages over other imaging techniques, including flexibility, speed, lower dose, and less ambiguity. Simulations show that the scattering of antiprotons by target nuclei reduces the correlation of image and target, but increasing the number of antiprotons used by less than an order of magnitude overcomes this effect.

WHEN COMPLICATED TECHNOLOGY is used in medicine, reassuring names are attached to the machines and techniques. One speaks of CAT scans, PET, and MRI (née NMR). Today I will talk about an imaging technique which has been discussed before at these meetings, ASTER, named after the wildflower. Since I am limited to about ten minutes, I will keep my talk simple. Here is the outline:

I. ASTER is ripe.

It is my contention that this flower has formed its fruit, and that not only is this fruit ripe for picking, but neither is it spoiled, as some have suggested.

A. ASTER uses antiprotons to image densities, and enough antiprotons are currently produced.

I will begin by reviewing ASTER.[1,2,3,4,5] ASTER is an acronym for Antiprotonic STERiography. In the ASTER imaging technique, still on the drawing board,

a beam of antiprotons are sent into a target. Collisions with electrons slow the antiprotons down, according to the well known stopping power

$$\frac{dE}{dx} = D\rho \frac{Z}{A}\frac{1}{\beta^2}\left[\ln \frac{2m_e c^2 \beta^2}{I(1-\beta^2)} - \beta^2\right],$$

where E is the kinetic energy of the particle, x is the distance traversed, Z is the proton number, A is the atomic mass, β is the speed relative to the speed of light, D is a constant approximately equal to 0.30707 MeV cm^2/g, ρ is the density, m_e is the electron mass, and I is an empirical function of Z which represents the average ionization potential of *all* electrons in an atom.[6]

The important features are the inverse square relation of the stopping power and the speed, which results in the Bragg peak, and the direct dependence on the density.

ASTER (a third definition here) means star (as in *). When the antiprotons have come to rest, they annihilate on a nucleon. Outward from the annihilation site stream various particles. In a bubble chamber photo, this event looks like a star (Fig. 1). Among the particles produced are charged pions. These are of sufficient energy to exit a target the size of the human body, and of sufficient mass to be deflected just a small amount before emerging. By detecting the directions of these pions and tracing their paths back to the intersection point with the antiproton path, the annihilation site can be determined precisely.

In this way, the range as a function of energy, $R(E)$, can be determined for the target, and $R(E)$ can be mapped to $\rho(R)$, a density profile.

Simulations of ASTER imaging confirm the estimates of the number of antiprotons needed for a scan, N:

$$N \sim \frac{\text{volume}}{\Delta x \Delta y \Delta z} \times \left(\frac{\sigma_V}{\Delta x}\frac{\rho}{\delta\rho}\right)^2$$

where the antiprotons are assumed to be travelling initially in the x direction, Δx, Δy, and Δz are the step sizes with which the beam is incremented in the various directions, σ_V is the error in determining the vertex, and $\delta\rho/\rho$ is the contrast resolution. To image a slice of $10 \times 10 \times 0.5\ \mathrm{cm}^3$ requires 2×10^5 antiprotons, for 1% contrast resolution and 1.5 mm spatial resolution within the slice. To image a whole

organ might require 20 slices, or 4×10^6 antiprotons, well within current production levels. The corresponding dose is about 200 μGy = 0.02 rads. Considering the biological effect of protons, the dose is about a tenth of the natural average annual background in the United States.[6]

B. ASTER has advantages over other imaging techniques.

ASTER appears to be lower in dose for comparable images than x-ray CT, as shown in a comparison of an ASTER simulation (Fig. 2) of the imaging of a Plexiglas and water phantom and the actual x-ray CT image of the same phantom. The phantom is an 8 cm diameter Plexiglas disk inside a 10 cm diameter Plexiglas cylinder filled with water. In the 3 mm thick disk the letter E is engraved to a depth of 1.5 mm. In the simulation, this cylinder was immersed in a rectangle filled with water. An x-ray CT scan (Fig. 3) was made of the cylinder in the plane containing the engraved disk. The dose imparted by the ASTER simulation was 100 μGy, over two orders of magnitude less than that imparted by the CT scan, approximately 30 mGy.

The table in Fig. 4 gives an overview of ASTER with other techniques. No one technique seems better than all the others for every situation. Similarly, ASTER will be complementary to the other techniques. Nonetheless, ASTER has potential for lower dose, higher resolution, faster scans, and imaging of elements as well as density. Perhaps most importantly, ASTER avoids the uncertainties introduced by back-projection techniques. Finally, ASTER is a flexible technique, as the following discussion shows.

C. The scattering of antiprotons does not spoil the image quality.

There has been some question as to whether the scattering of the antiprotons off the nuclei will irretrievably lower the resolution of ASTER. In water, the antiproton beam spreads out with a width of $\sigma_y = 0.0195R^{0.966}$. There is a well defined centroid, so resolution can be maintained by increasing the number of antiprotons used. In heterogeneous media, one can imagine that some of the antiproton paths will sample regions of different density, hopelessly convoluting the relation of stopping position to density profile. However, this is not the case, as I will show by considering individual antiproton paths in water, and by showing successful images

of highly heterogeous targets.

In terms of individual paths, it is reasonable that transverse scattering will not ruin ASTER images. This is because the average density in a small region is obtained from the difference in the mean stopping positions of two cohorts of antiprotons with nearly the same energy. In engineering terms, one would say that one is looking at the difference between two integrals, and integration suppresses the noise.

Fig. 5 shows the paths of many antiprotons in water. The horizontal (longitudinal) and vertical (transverse) scales are the same, and the three dimensional paths have been projected onto the plane. Next, I considered only the antiprotons stopping in a small transverse bin. If the initial energy of the antiprotons is varied just a bit, the antiprotons still sample the same region in space. That is, a group of paths stopping about R tends to sample the same portion of the target as a group of paths stopping about $R + \Delta R$. This is shown in Figs. 6, 7, 8, and 9. This is true even though I have included the finite beam width in the Monte Carlo.

The sampling of the same region in space by the antiprotons is a statistical phenomenon. Therefore, it suggests that the scattering problem can be overcome by increasing the number of antiprotons, a method already required by the straggling. To test this, I simulated the imaging of a "random" target, which was the most heterogeneous thing I could think of. ASTER is a very flexible tool, and the imaging can be oriented to best advantage. I imaged this random slice longitudinally, so that each antiproton travelled in the slice. And I imaged the random slice transversally, so that the antiprotons travelled through a centimeter of water before encountering the slice perpendicular to the plane. The transverse orientation is shown in Fig. 10, the random target in Fig. 11, and the transverse image in Fig. 12.

The heterogeneous nature of this target convolutes the longitudinal image more than the transverse image. So for a given number of antiprotons, the transverse image will be better.

The quality of the image can be shown by correlating the image and the target. I define a correlation number C^{-1}, where

$$C^2 \equiv \sum_j \sum_k (\rho_{1jk} - \rho_{2jk})^2 / n,$$

ρ_{1jk} and ρ_{2jk} are the densities of the target and image at the jkth pixel, and n is the number of pixels used for comparison. The correlation increases as the number of antiprotons increases for both the transverse and longitudinal imaging (Fig. 13). The correlations match when about four to nine times as many antiprotons are used in the longitudinal case as in the transverse case. So increasing the number of antiprotons by an order of magnitude will overcome severe heterogenous effects. After this increase is made, ASTER still imparts an order of magnitude less dose than x-ray CT.

If the decrease in correlation is due to the heterogeneous convolutions, than the effect will begin to show up in the transverse case as the slice is lowered deeper into the water, so that the antiproton beam is more spread out when it reaches the slice. This is shown in Fig. 13 by the decrease in correlation between transverse image and target as the depth increases.

References

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2 Gray, L., and Kalogeropoulos, T. E. *IEEE Trans Nucl Sci* **NS-29** (1982) 1051–1057.

3 Kalogeropoulos, T.; Archambeau, J.; Bassano, D.; Bennett, G.; Gottchalk, B.; Gray, L.; Koehler, A.; Muratore, R.; and Urie, M. In *Proceedings of the RAND Workshop on Antiproton Science and Technology, October 6–9, 1987*, edited by B. W. Augenstein, B. E. Bonner, F. E. Mills, and M. M. Nieto. Teaneck, NJ: World Scientific, 1988.

4 Kalogeropoulos, Theodore E., and Muratore, Robert. *Nuclear Instruments and Methods* (1989) *in press.*

5 Muratore, Robert. Ph.D. dissertation, Syracuse University, 1988.

6 Particle Physics Group. *Phys Lett* **B204** (1988) 1–486.

14

Fig.1

ASTFRt.flx.11; 18-NOV-1988 22:12:03.39

total # pbars stopping = 194811
total # pbars injected = 212973

file = E.dat.3 5σ
height above slice (cm) = 1.000
slice width along beam (cm) = 0.500 2×10^{-4} Gy
segment length (cm) = 0.050
percent error in density = 1.000
white, black densities (g/cm**3) = 1.100 1.050
horiz, vert magnifications = 1.000 1.000

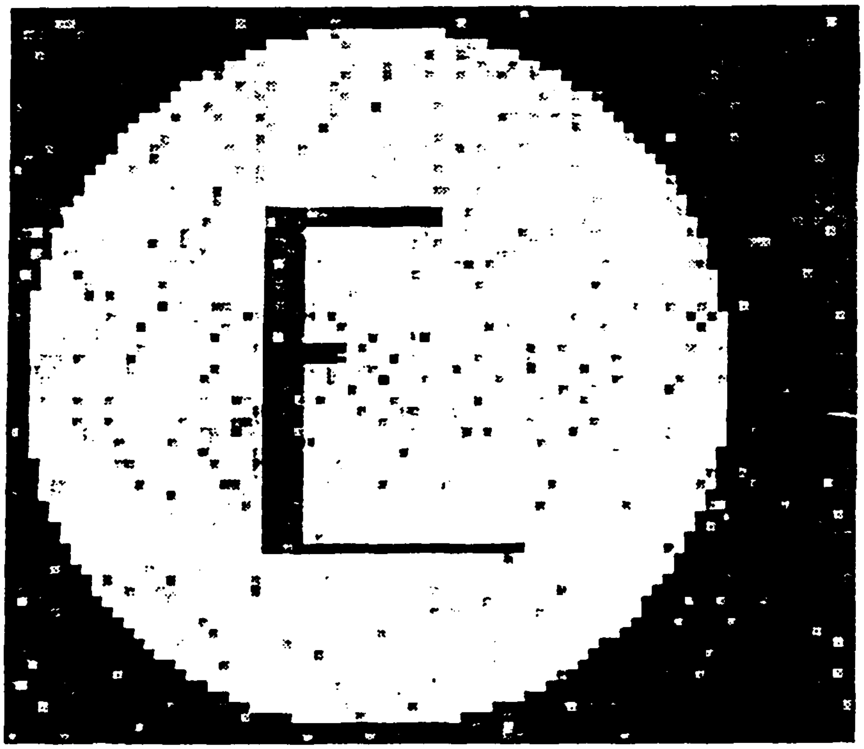

Fig.2

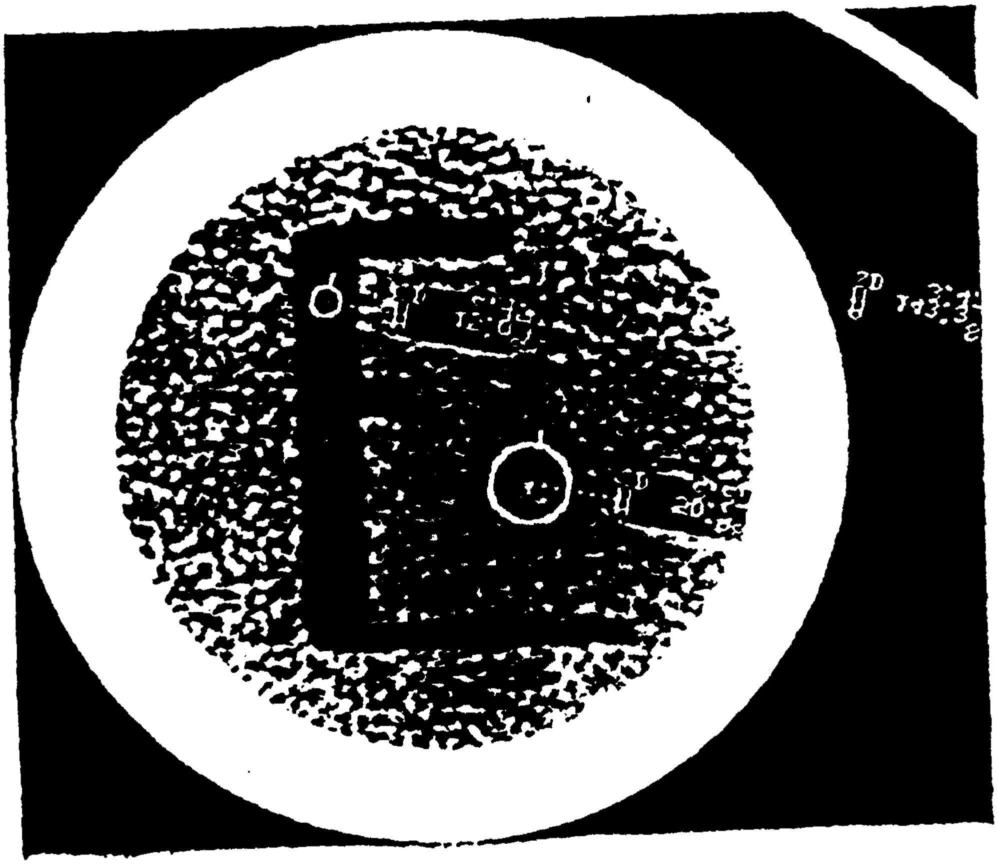

Fig. 3

Table: IMAGING TECHNIQUES

system	CT[a]	MRI	ultrasound[a]	PET	ASTER
detected	transmitted x-rays	rf from induced emf	acoustic echoes	γ-rays	$\pi^{\pm}$ (& x-rays)
imaged	electron density	induced nuclear magnetization	discontinuities in speed of sound	tagged chemical concentration	electron density (& elements)
structure	"	"	density, elasticity	biochemical	"
inference	transform	tran. or ver.	transform	transform	vertex
source	x-ray tube	precession	transducer	decay	$\bar{p}$
detector	x-ray det.	rf coil	transducer	γ-ray det.	drift ch.
spatial resolution	0.5 mm	2 mm	2 mm	$\sim$ 1 mm	$<$ 0.5 mm
temporal resolution	0.5 s	0.1 to 100 s	0.01 s	10 to 1000 s	$<$ 0.01 s
dose	0.03 Gy	(nonionizing)	(nonionizing)	varies	0.0001 Gy

[a] Fullerton, Gary D., and Zagzebski, James A., eds. *Medical Physics of CT & Ultrasound*. New York: American Institute of Physics, 1980.

Fig. 4

follow.for.26

3-MAY-1989 11:00:43.39

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0.100	1.000	7.500	0.050	1.000	20	10.000	-10.000

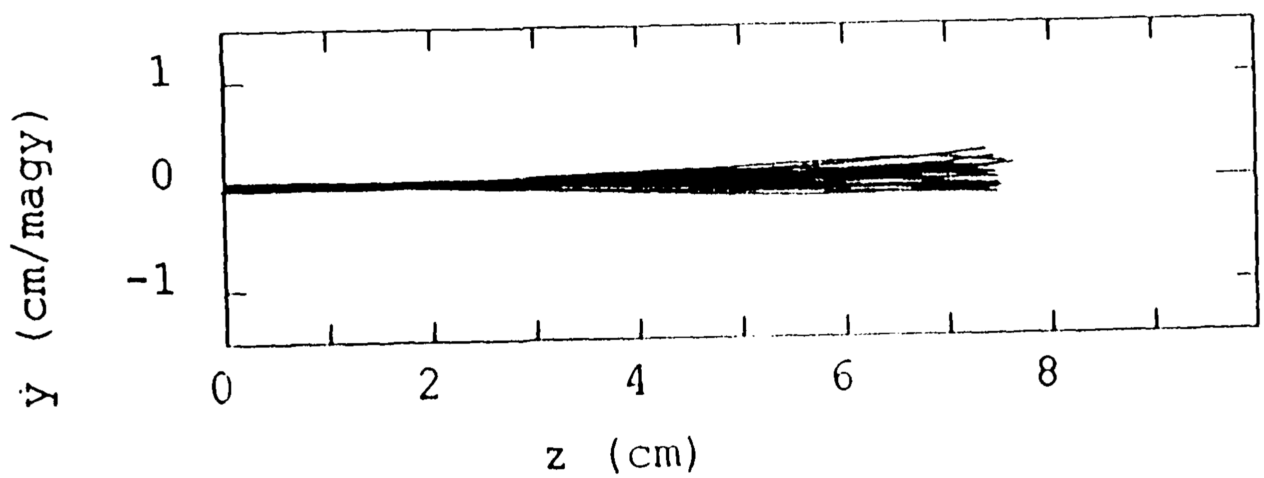
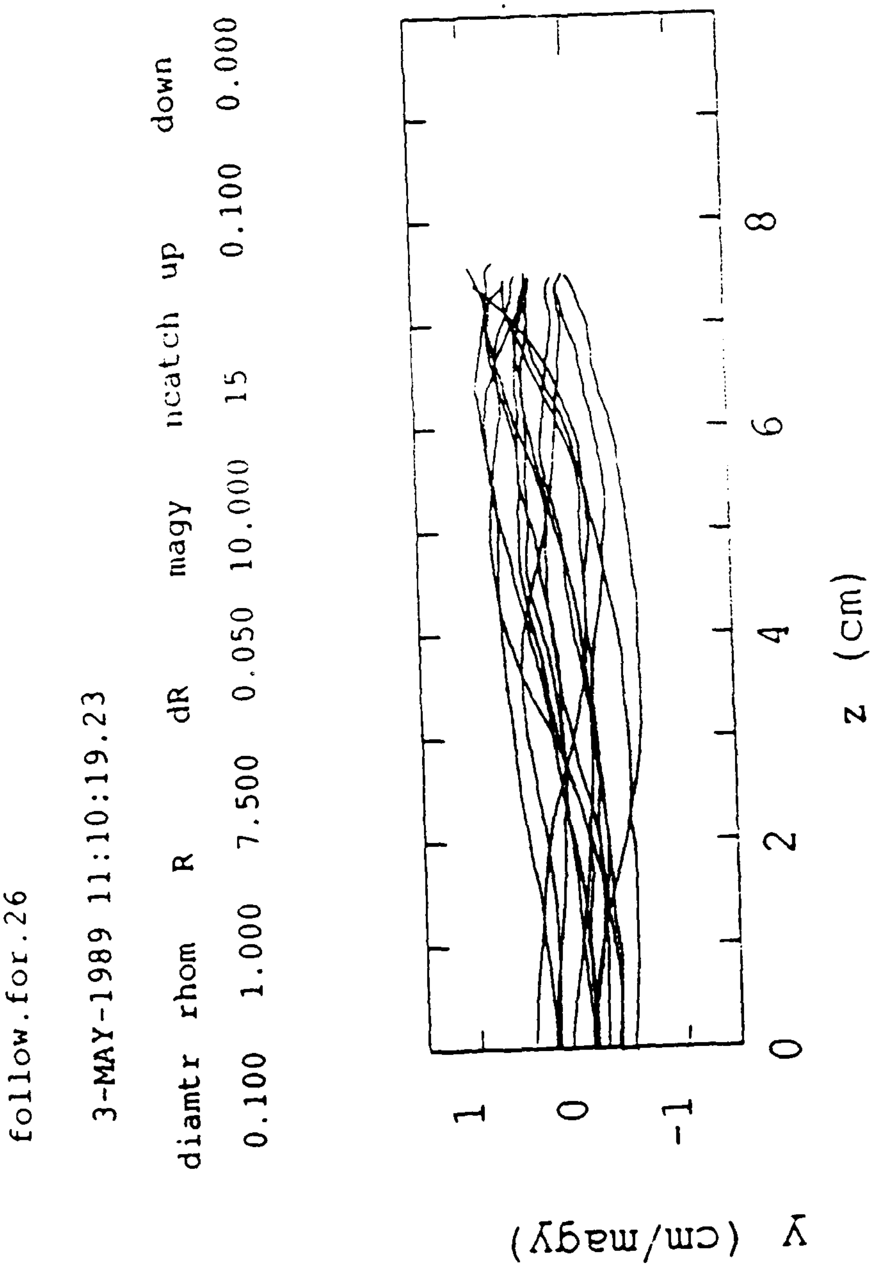


Fig.5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1
0
-1
y (cm/magy)
0
2
4
6
8
z (cm)

Fig.6

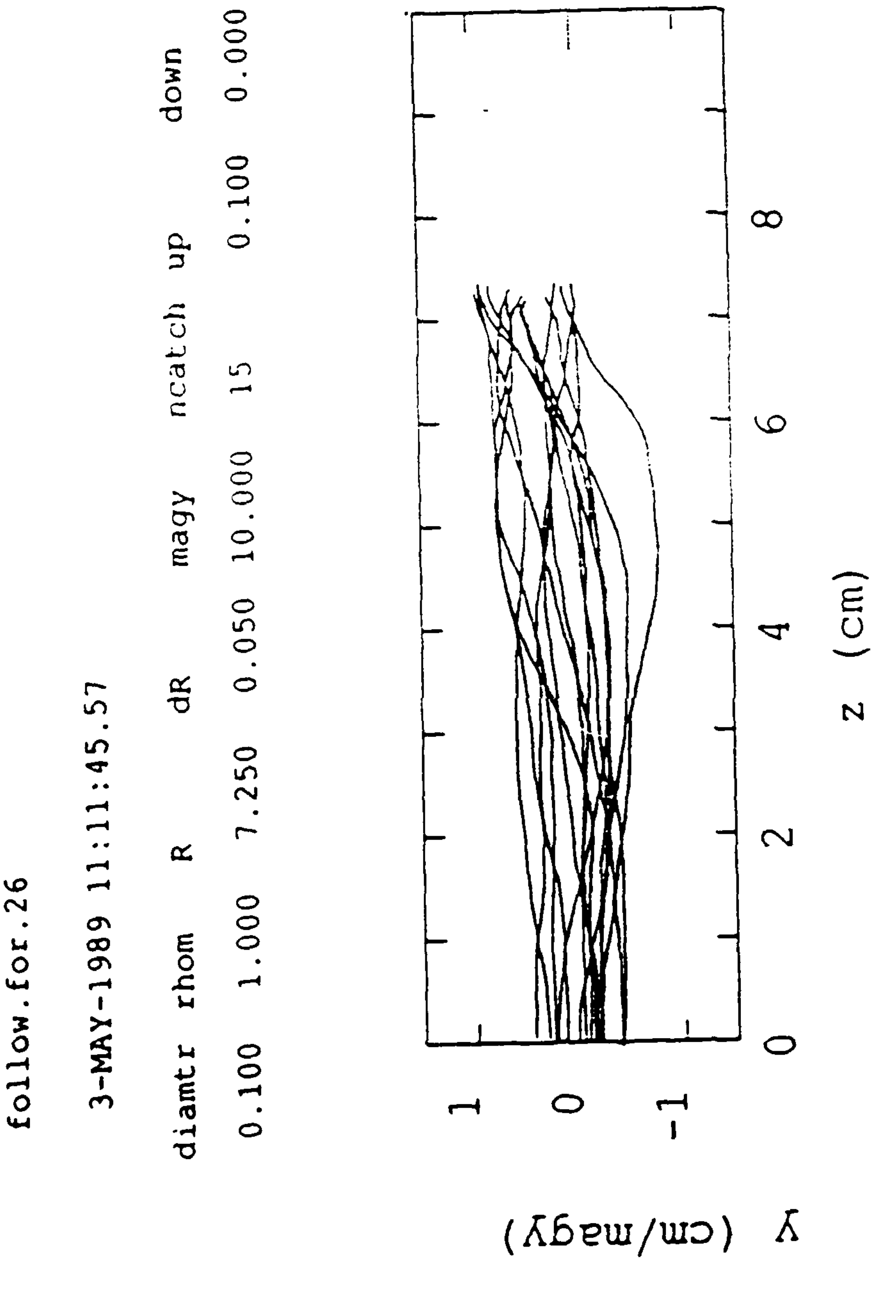

follow.for.26
3-MAY-1989 11:11:45.57
diamtr rhom R dR magy ncatch up down
0.100 1.000 7.250 0.050 10.000 15 0.100 0.000
1
0
-1
0
2
4
6
8
z (cm)
y (cm/magy)

Fig.7

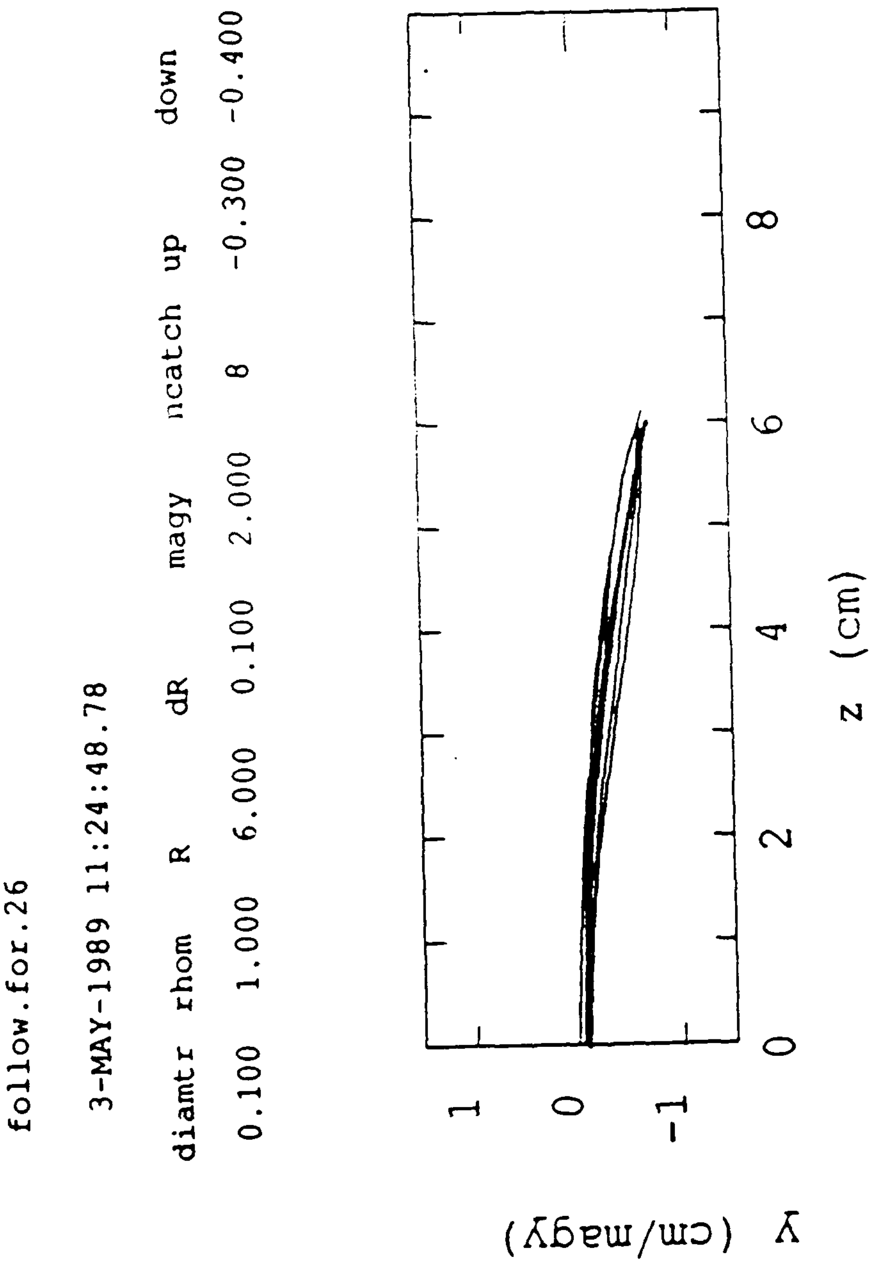

follow.for.26
3-MAY-1989 11:24:48.78
diamtr rhom R dR magy ncatch up down
0.100 1.000 6.000 0.100 2.000 8 -0.300 -0.400
y (cm/magy)
z (cm)

Fig.8

follow.for.26

3-MAY-1989 11:27:25.99

diamtr	rhom	R	dR	magy	ncatch	up	down
0.100	1.000	6.500	0.100	2.000	8	-0.300	-0.400

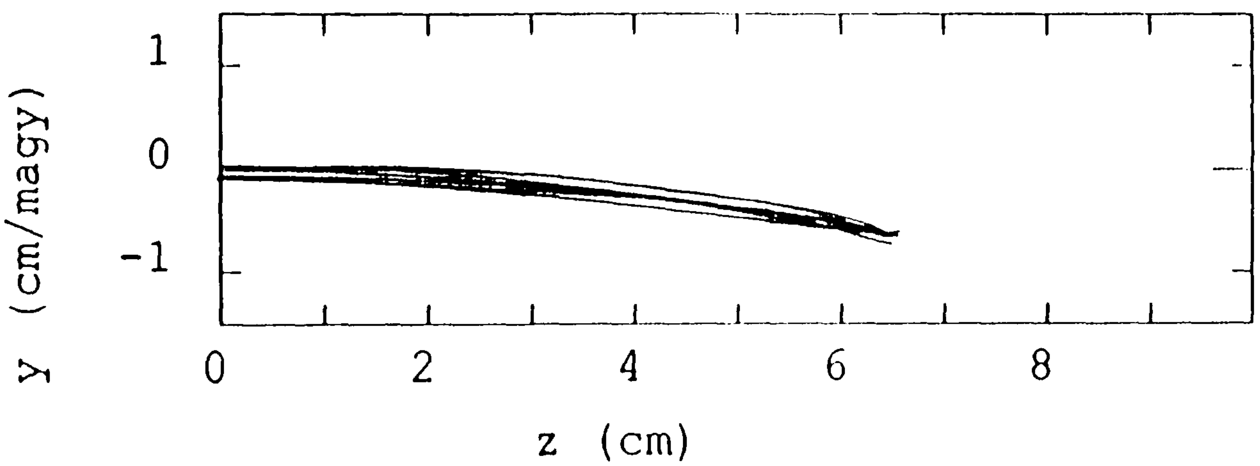


Fig.9

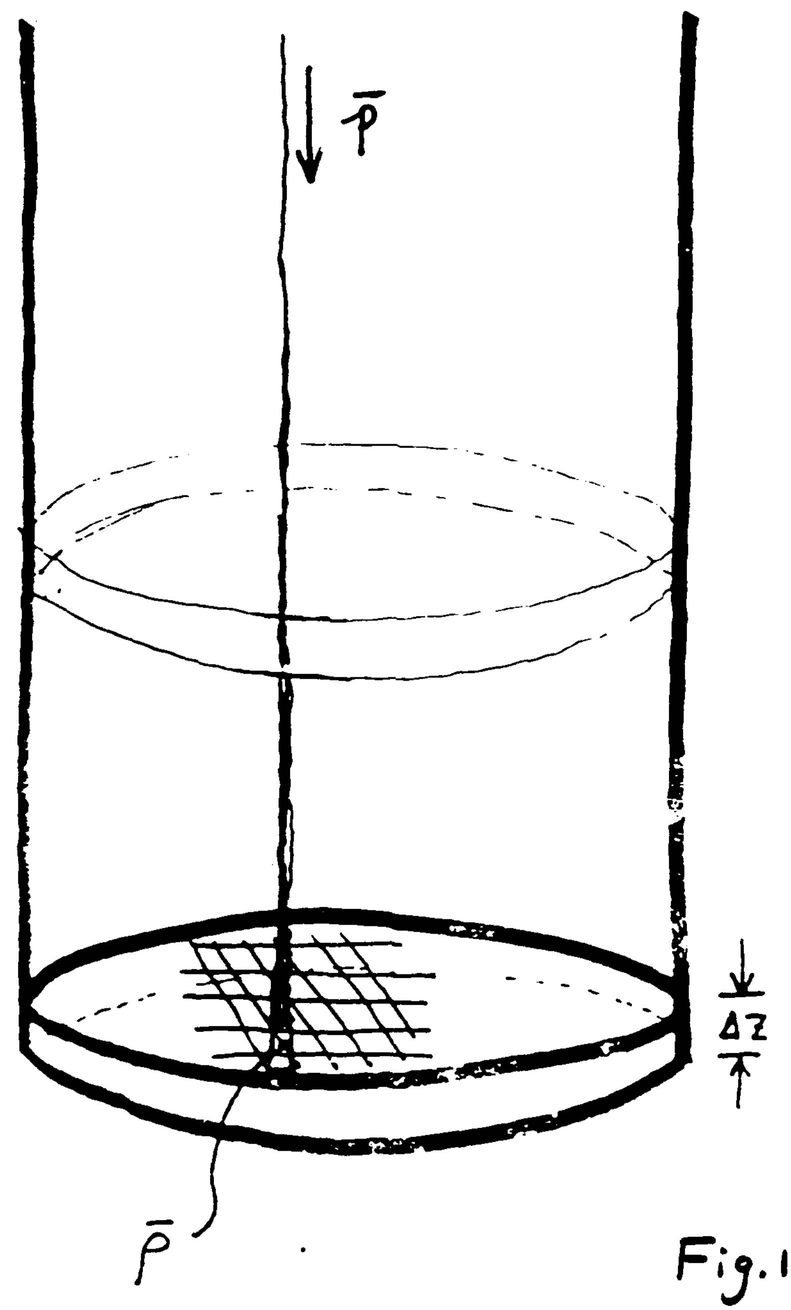


Fig. 10

23

ASTERt.flx.11　　　1-NOV-1988 10:11:26.53

file = random2.dat.1

white, black densities (g/cm**3) = 1.050 0.950
horiz, vert magnifications = 1.000 1.000

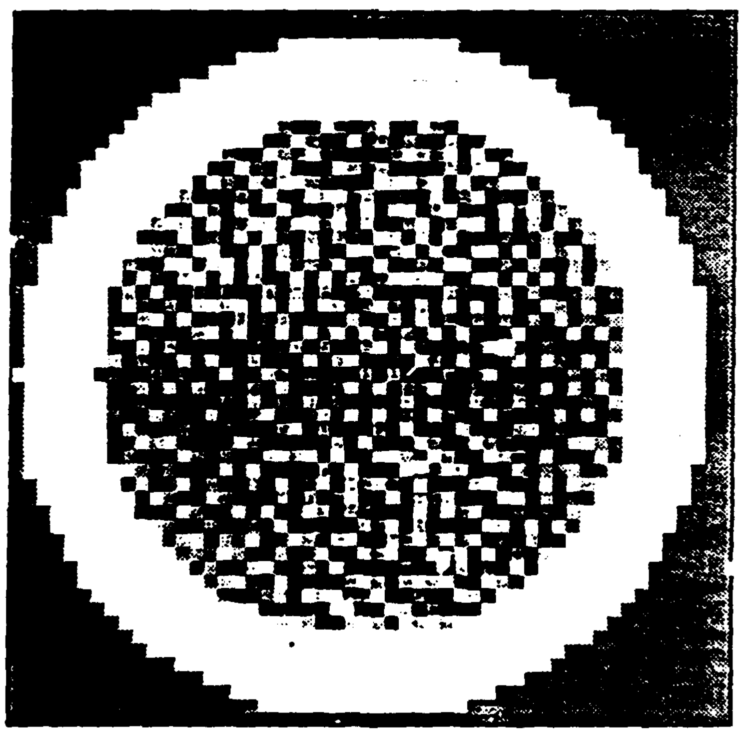


Fig. 11

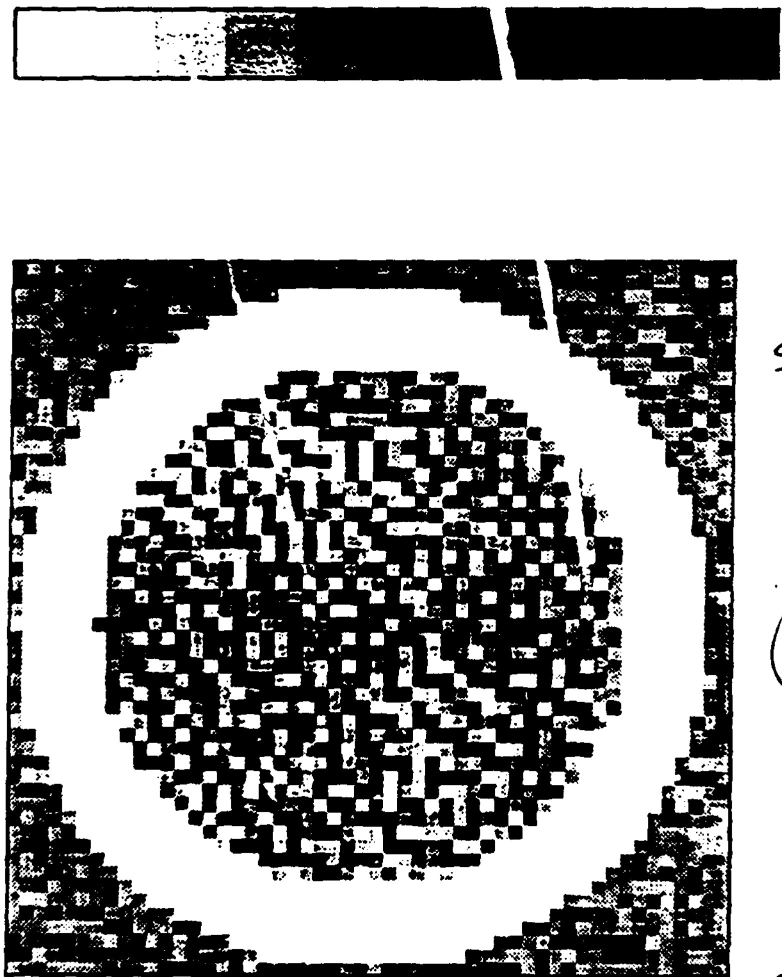
ASTERt.flx.11 2-NOV-1988 13:20:56.24

file = astert.dat.7

target = random2.dat.1

white, black densities (g/cm**3) = 1.050 0.950

horiz, vert magnif cations = 1.000 1.000



$\frac{\delta\rho}{\rho} = 1\%$

depth = 1 cm

slice thickness = 0.2 cm

$N_{\bar{p}} = 4.7 \times 10^5$

$\left(\frac{N_{\bar{p}}}{\text{pixel}}\right) = 175$

segment length = 0.2 cm

Fig.12

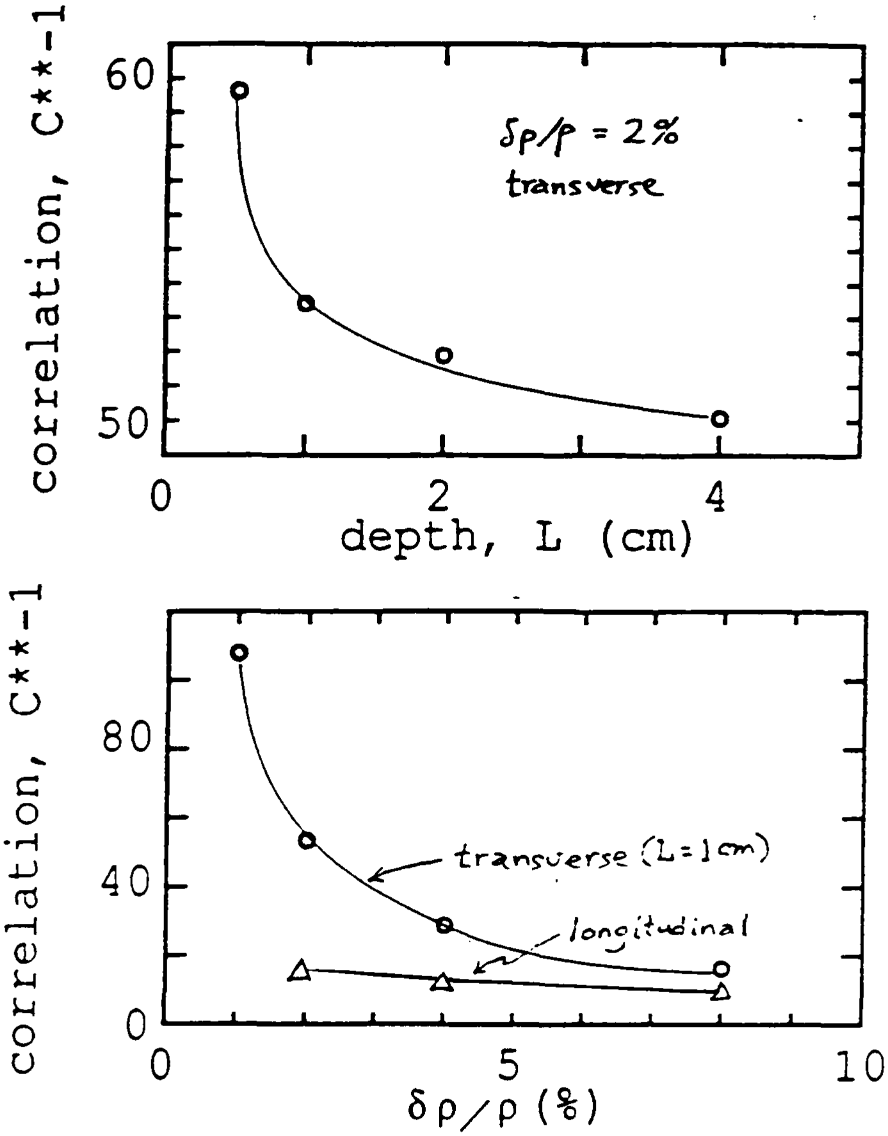

correlation, C**-1
60
50
δρ/ρ = 2%
transverse
0
2
4
depth, L (cm)
correlation, C**-1
80
40
0
transverse (L=1cm)
longitudinal
0
5
10
δρ/ρ (%)

Fig.13

Pbar TESTING OF HYDROGEN EFFECTS
IN SEALED CARBON-CARBON COMPOSITES

HARRIS CARTER

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PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

Rationale and Concept for NDE Application of Antiprotons (u)

- Early applications might include non-destructive evaluation (NDE) of aerospace materials
- Advanced carbon-carbon structures present
  - ✔ Special NDE problems (e.g. need for "backscatter" rather than transmission)
  - ✔ Special features suggesting $\bar{p}$'s for NDE (vs ultrasound or x-rays)

__Assumption:__ Useful Sources will be $\bar{p}$'s trapped at ≤ Kev energies or stabilized in chemical complexes

__Suggested NDE mode:__ Use low energy $\bar{p}$'s as portable source of Π^- mesons

__Purpose:__ Determine atomic ratios O/C and H/C deep in Carbon - Carbon structures

Annihilation at source: $\bar{p} + p \rightarrow \Pi^0 + \Pi^+ + \Pi^-$ (K.E. ~ 250 Mev)

__Reactions:__

Reactions in Target: Π^- (stopped) + p → n + γ (129 Mev)

Π^- (stopped) + O → Π^-O mesic atom + 178 Kev x-ray

UNCLASSIFIED

BN06752

ADVANCED CARBON-CARBON: EDGE VIEW SHOWING CRACKS AND VOIDS

B18084

© 1989 GDFW

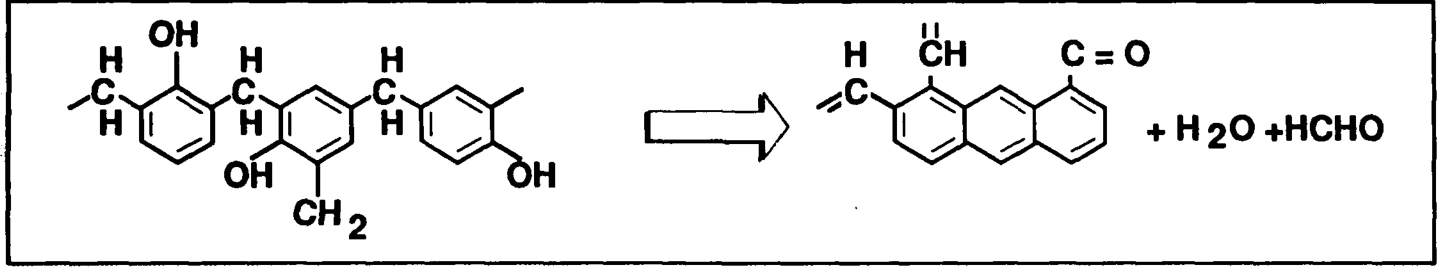
ADVANCED CARBON-CARBON: HIGHER MAGNIFICATION SHOWING INCOMPLETE REACTION IN CONVERSION COAT

B18087

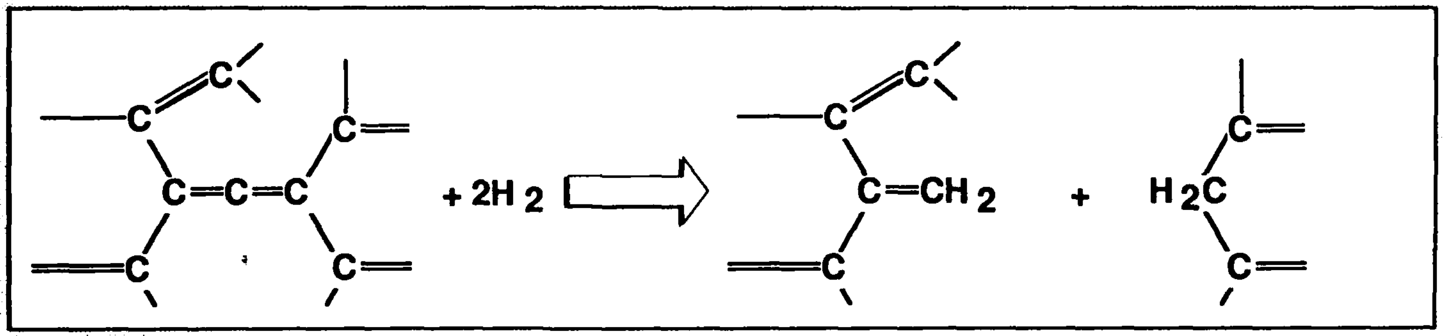
© 1989 GDFW

Need for NDE to Sample Atomic Ratios in Thick C-C Structures (u)

a) Residual Oxygen and Hydrogen Indicate incomplete pyrolysis



b) Hydrogenation of C-C in high temp H_2 environment is possible reversion mechanism



- Energetic Π^- from $\bar{p}$ + p annihilation could reveal (a) poor cure or (b) in use hydrogenation at points deep in Carbon-Carbon structure by γ and x-ray backscatter

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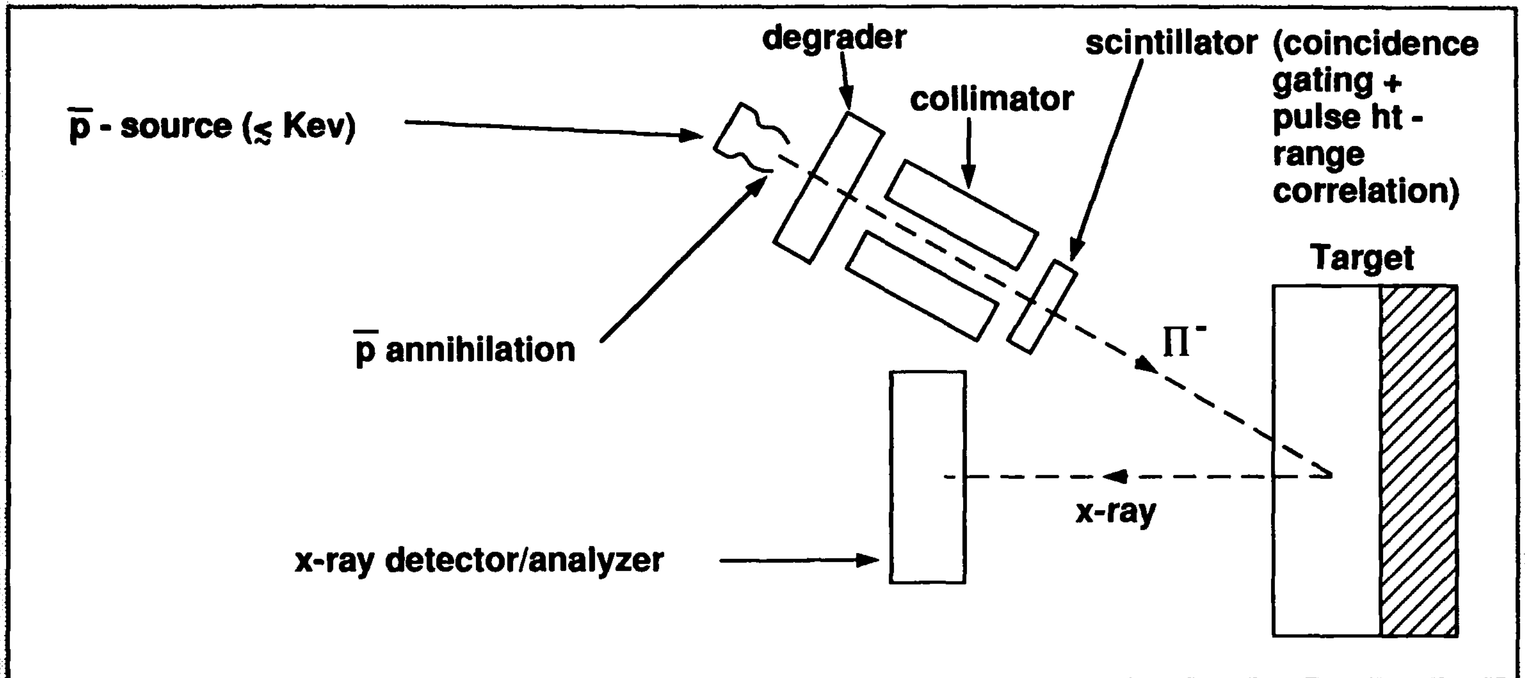
BN06753

Proposed Deep-Target Chemical Diagnostics using Π^- from $\overline{p}$ Annihilation (u)



- In practical case, x-ray counts from 10^8 $\overline{p}$ might not exceed 10^3 ; but:
  - ✔ Effective clutter would be low due to gating & low count rate
  - ✔ X-rays from, say, Π^- O could be easily counted and identified

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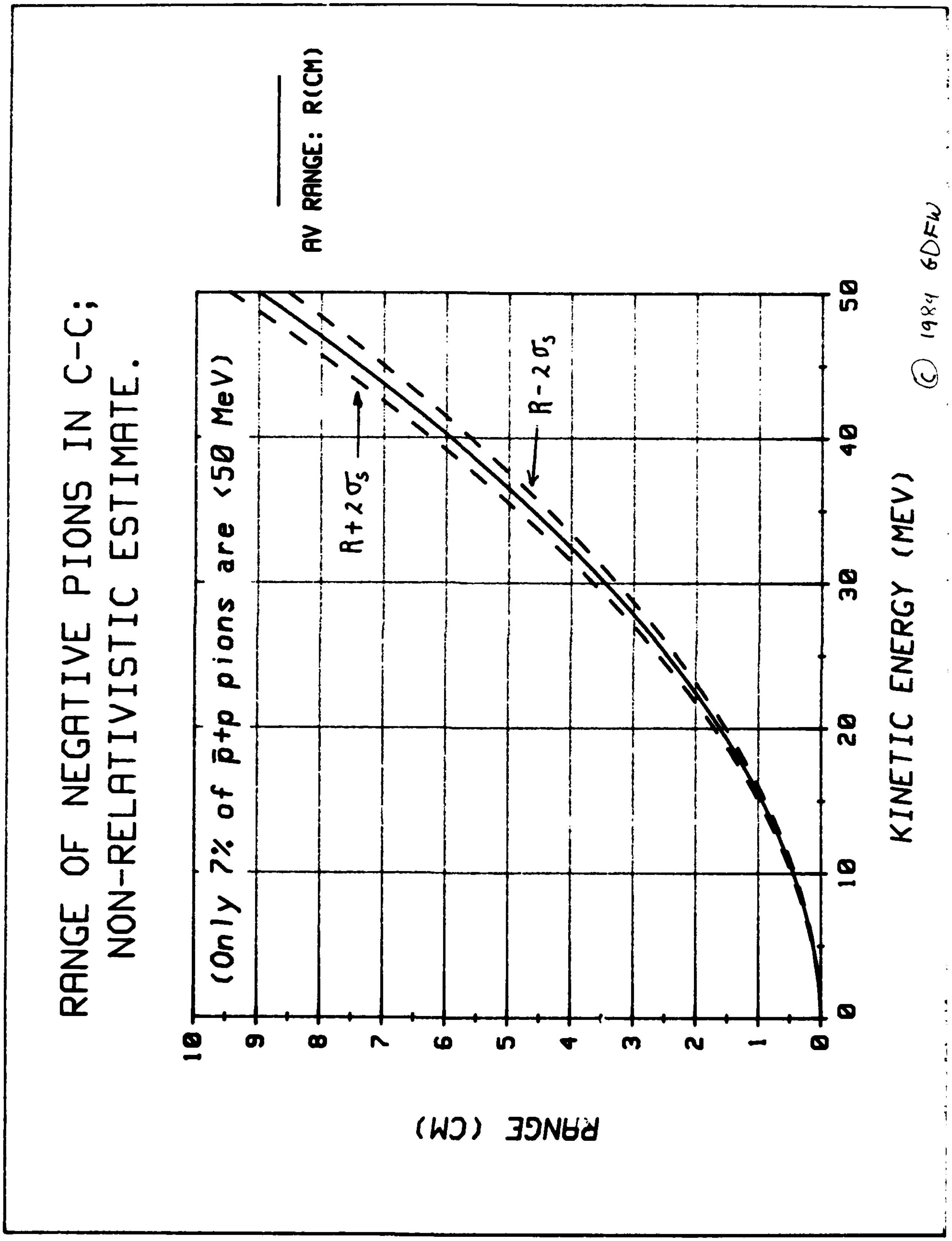
BN06754


RANGE OF NEGATIVE PIONS IN C-C;
NON-RELATIVISTIC ESTIMATE.
(Only 7% of $\bar{p}$+p pions are <50 MeV)
AV RANGE: R(CM)
R+2σ_s
R-2σ_s
RANGE (CM)
KINETIC ENERGY (MEV)
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
© 1984 GDFW

X-Rays from 2 P→IS Transitions in Π^- Mesic Atoms and Attenuation in Carbon-Carbon (u)

Π^- Atom	X-ray energy (KEV)	Mass abs coef in C-C (ρ = 1.5 gm/cc): $\mu(cm^{-1})$
H	2.4	~ 150
C	100	.23
O	178	.19
(Fluorescent X-ray fom normal O atom)	(.65)	(~1000)

X-ray line degradation through 5 cm of C-C:
C(100 Kev) = 1/3.1
O(178 Kev) = 1/2.6

- Oxygen, implying poor cure, could be identified in thick (e.g., 5 cm) C-C structures
- X-rays from Π^- H would not be observed; presence of H might be inferred from Π^- C reduction due to competitive orbital capture of Π^- by H

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BN06751

THEORETICAL POTENTIAL OF ANTIPROTONS IN RADIATION ONCOLOGY

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Lahey Clinic Medical Center
Boston MA

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

Potential Radiation Damage

A) Direct Effects - Damage DNA Itself

B) Indirect Effects - Form Free Radicals

$OH\cdot$

$DNA\cdot$

$DNA\cdot + O_2 \longrightarrow DNAOO\cdot$

$$\text{Oxygen Enhancement Ratio} = \frac{\text{Dose Hypoxic}}{\text{Dose in Oxygen}}$$

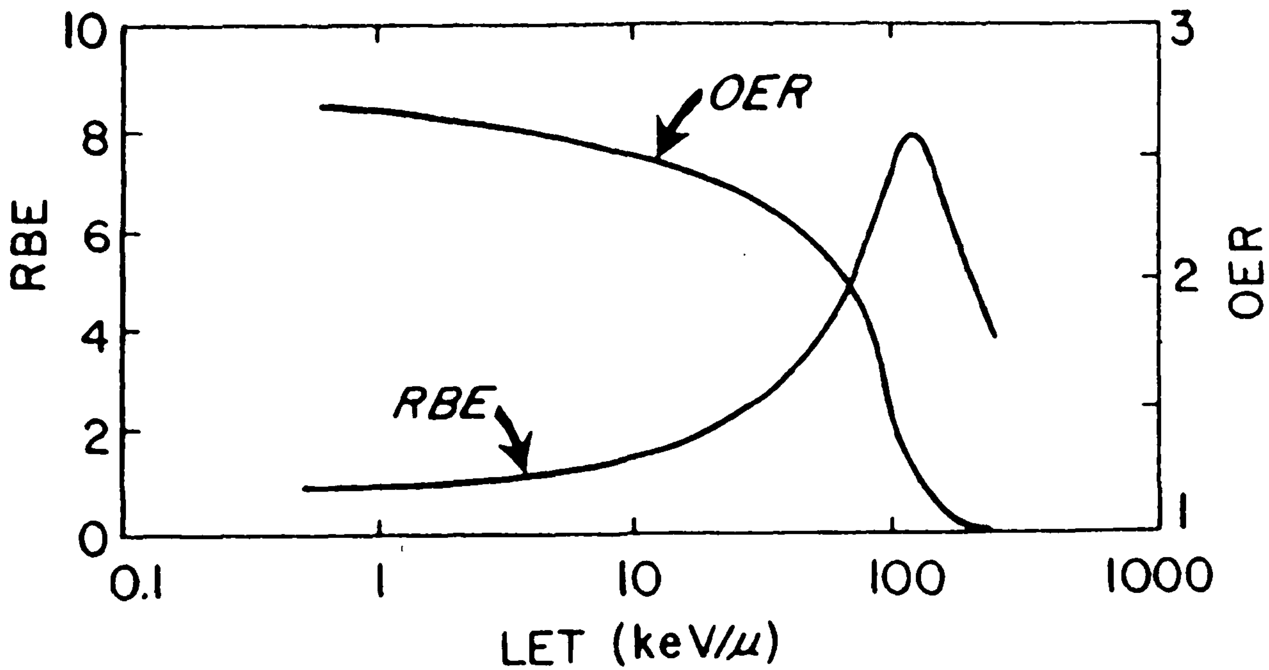
x-rays OER = 2.5-3

neutrons OER = 1.6

$$\text{Relative Biological Effect} = \frac{\text{Dose}_{250}}{\text{Dose}_{r}}$$

RBE varies with:
1) system or tumor studied
2) amount of damage in that system

FIG. 6–11. Variation of the OER and the RBE as a function of the LET of the radiation involved. The data were obtained by using T_1 kidney cells of human origin, irradiated with various naturally occurring α-particles or with deuterons accelerated in the Hammersmith cyclotron. Note that the rapid increase of RBE and the rapid fall of OER both occur at about the same LET, namely about 100 keV/μ. (Redrawn from Barendsen GW: in Proceedings of the Conference on Particle Accelerators in Radiation Therapy. US Atomic Energy Commission, Technical Information Center, LA-5180-C, October 1972, pp 120–125)



Source: Hall, Eric J., Radiobiology for the Radiologist, 2nd. ed., Harper & Row, Philadelphia, pg. 109.

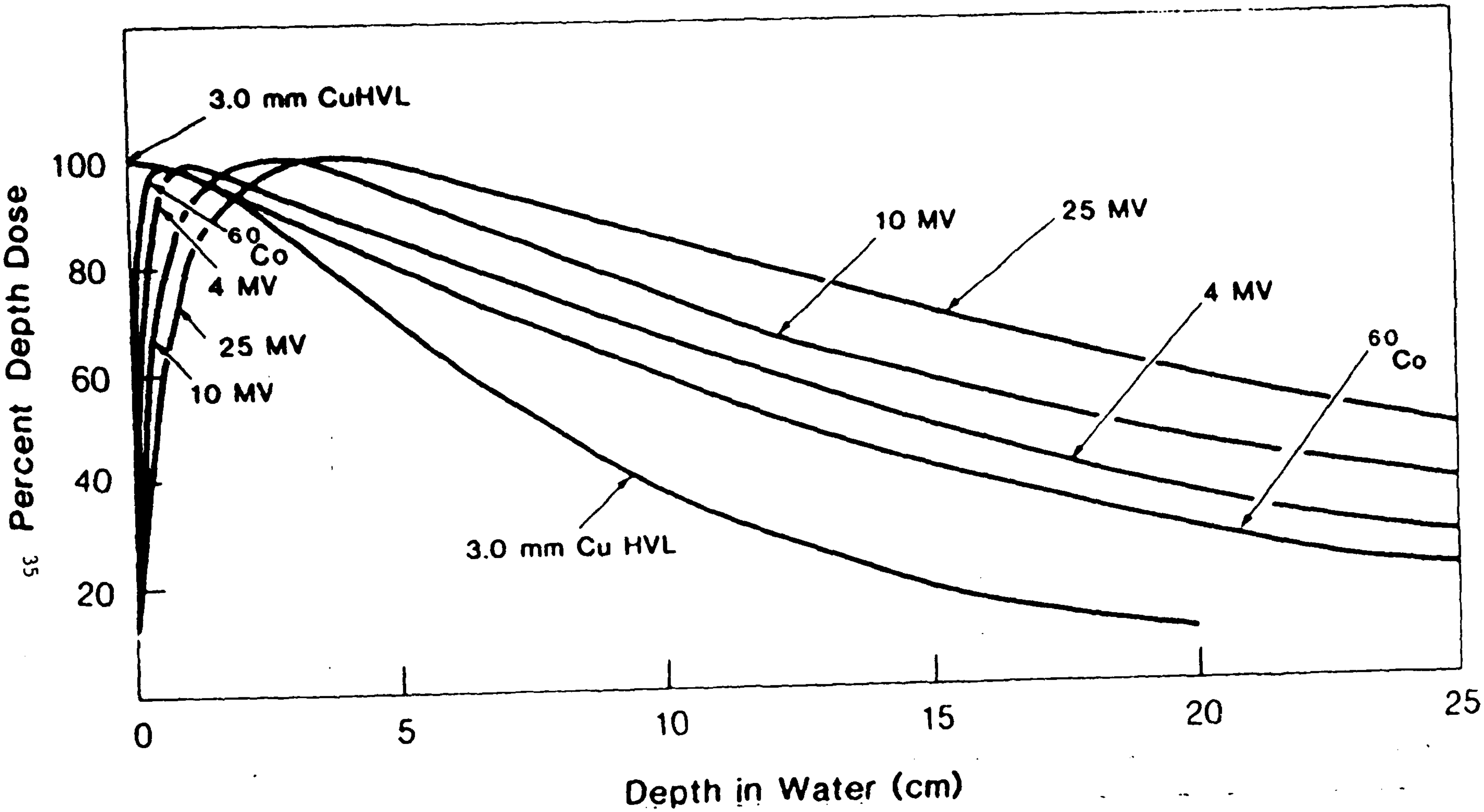


Figure 9.3. Central axis depth dose distribution for different quality photon beams. Field size, 10 × 10 cm; SSD = 100 cm for all beams except for 3.0 mm Cu HVL, SSD = 50 cm. Data are from Reference 13 and the Appendix.

Source: Khan, Faiz M., The Physics of Radiation Therapy, Williams & Wilkins, Baltimore, pg. 161.

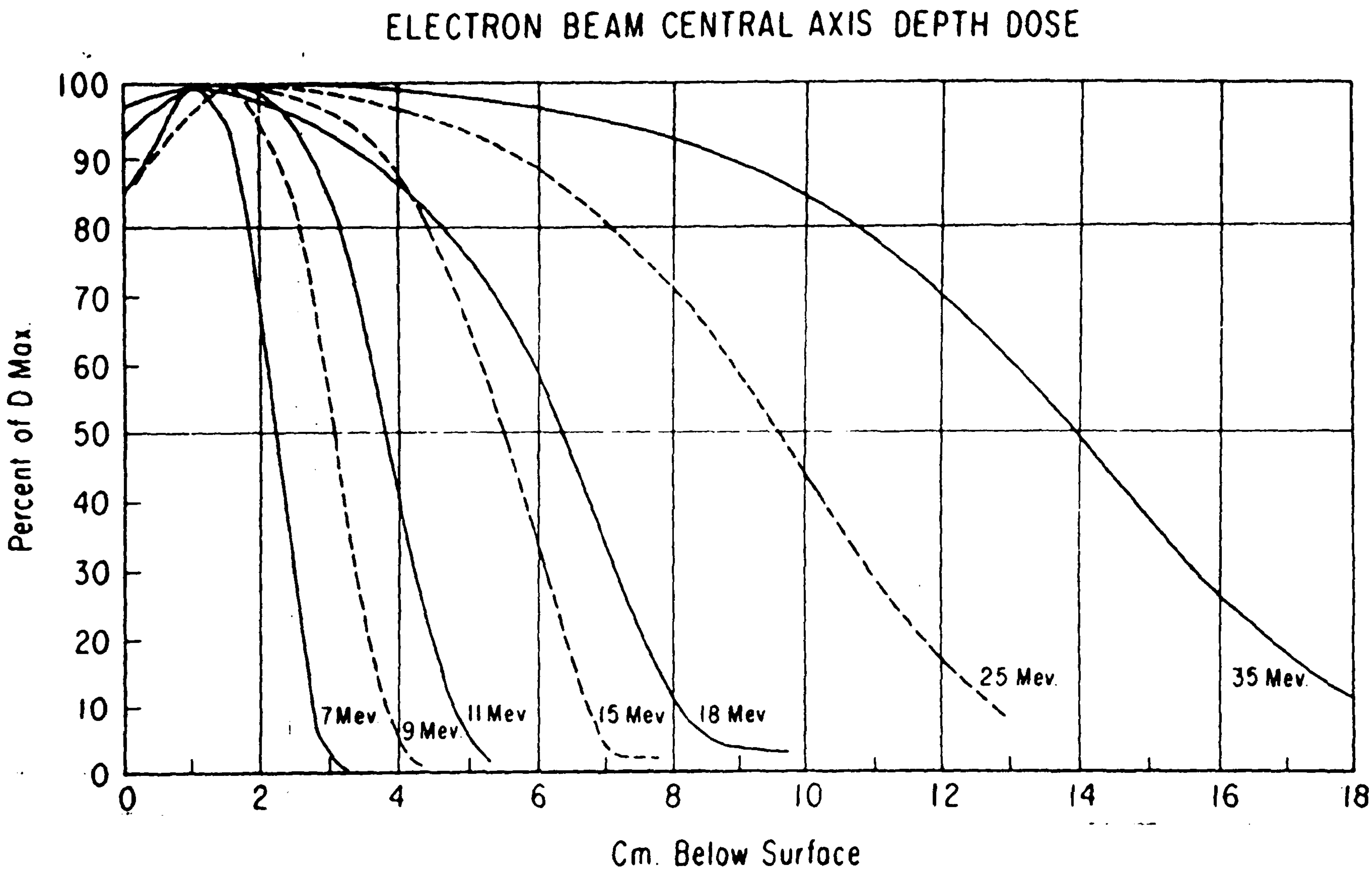
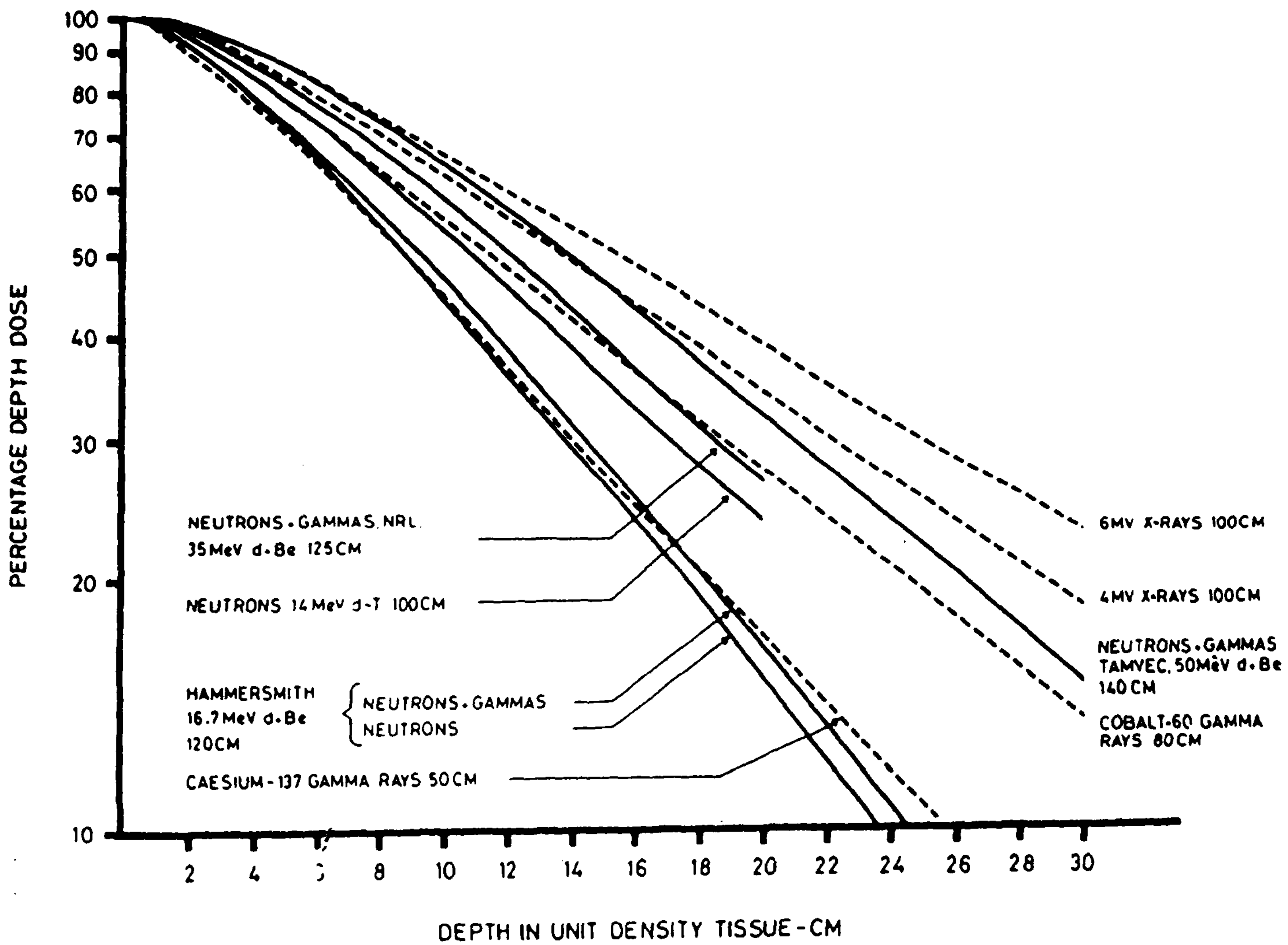


Figure 14.8. Comparison of central axis depth dose distributions of the Sagittaire linear accelerator (continuous curves) and the Siemen's betatron (dashed curve). [Reprinted with permission from: Tapley (35).]

Source: Khan, pq. 314.



Source: Hall, pg. 296.

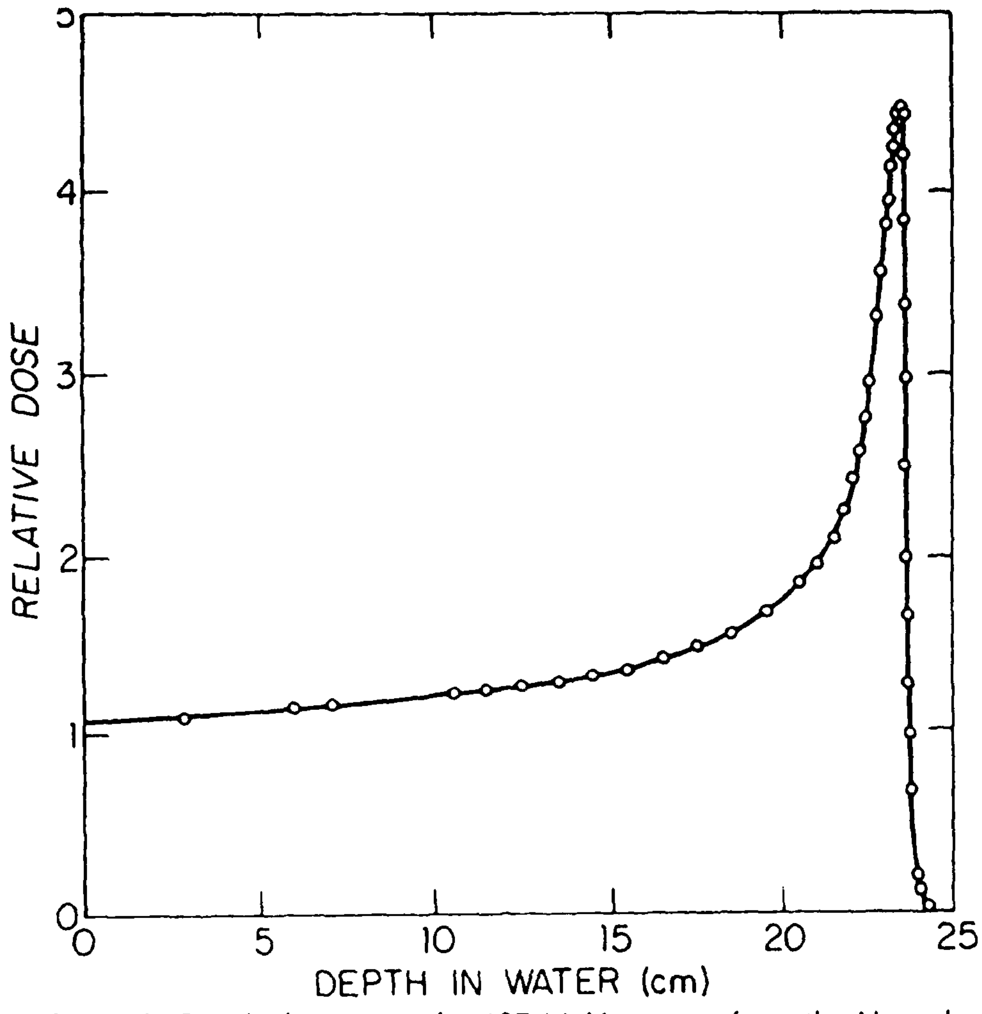


FIG. 15–6. Depth-dose curve for 187-MeV protons from the Uppsala synchrocyclotron. The dose reaches a sharp peak at a depth of about 23 cm. (Redrawn from Larsson B: Br J Radiol 34:143–151, 1961)

Source: Hall, pg. 311.

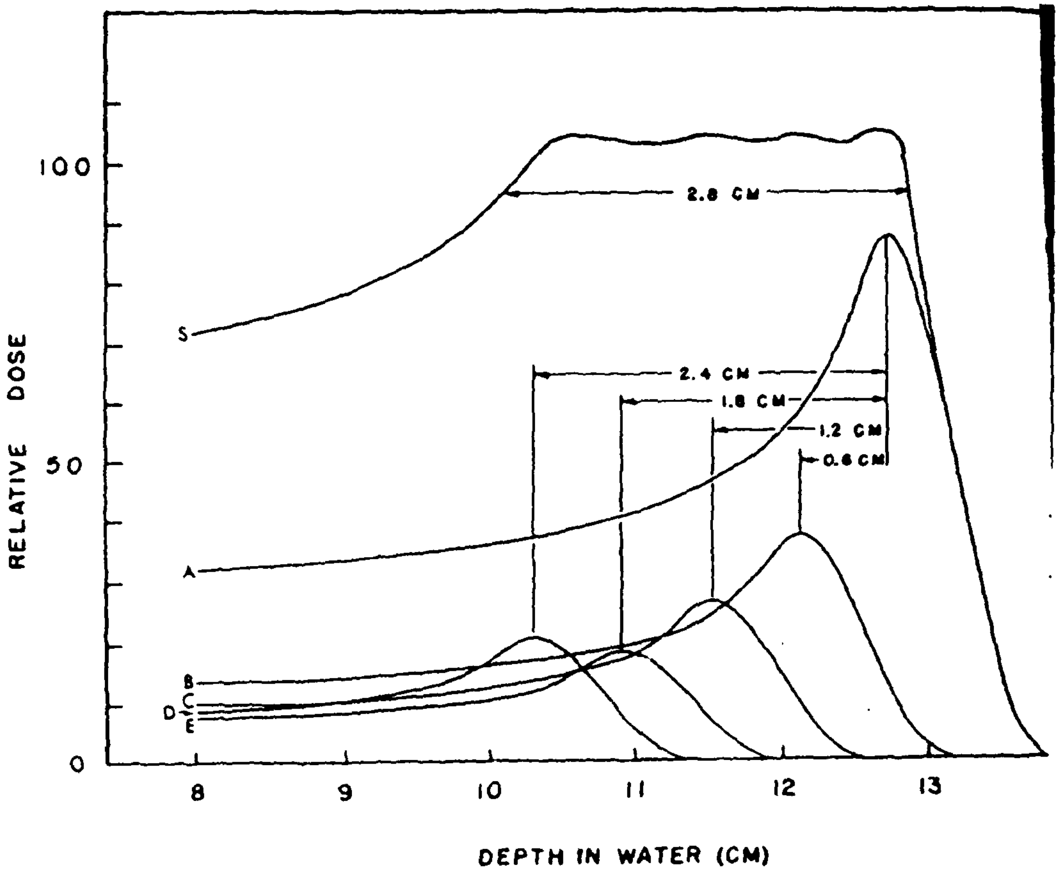


FIG. 15–7. Illustrating the way in which the Bragg peak for a proton beam can be spread out. Curve A is the depth-dose distribution for the primary beam of 160-MeV protons at the Harvard cyclotron, which has a half-width of only 0.6 cm. Beams of lower intensity and shorter range, as illustrated by curves B, C, D, and E, can be added to give a composite curve *S*, which results in a uniform dose over 2.8 cm. The broadening of the peak is achieved by passing the beam through a rotating wheel with sectors of varying thickness. (Redrawn from Koehler AM, Preston WM: Radiology 104:191–195, 1972)

Source: Hall, pg. 312.

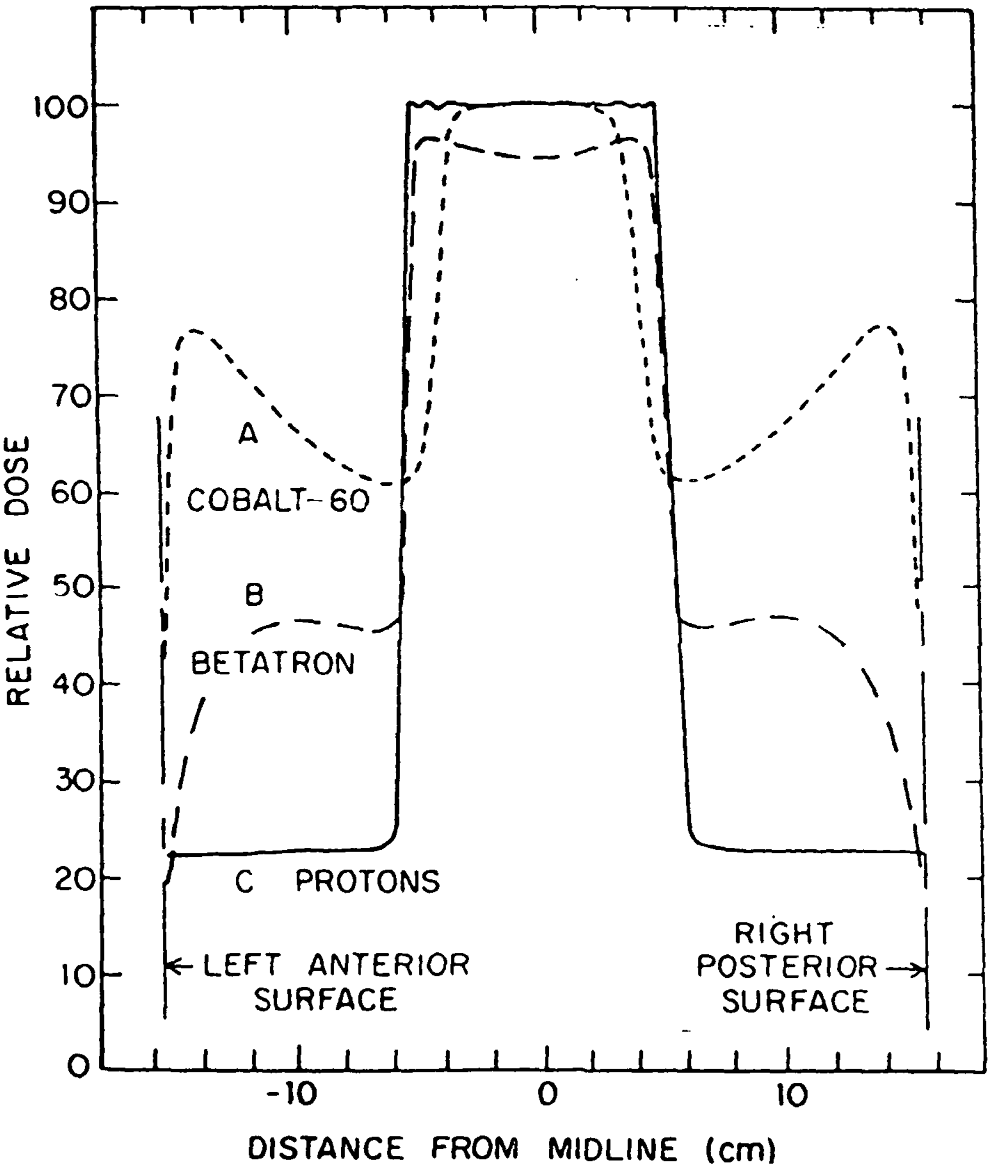
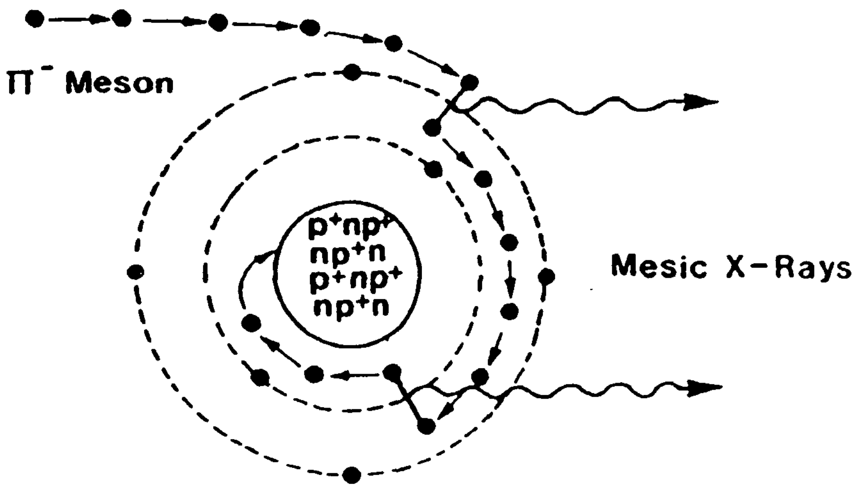
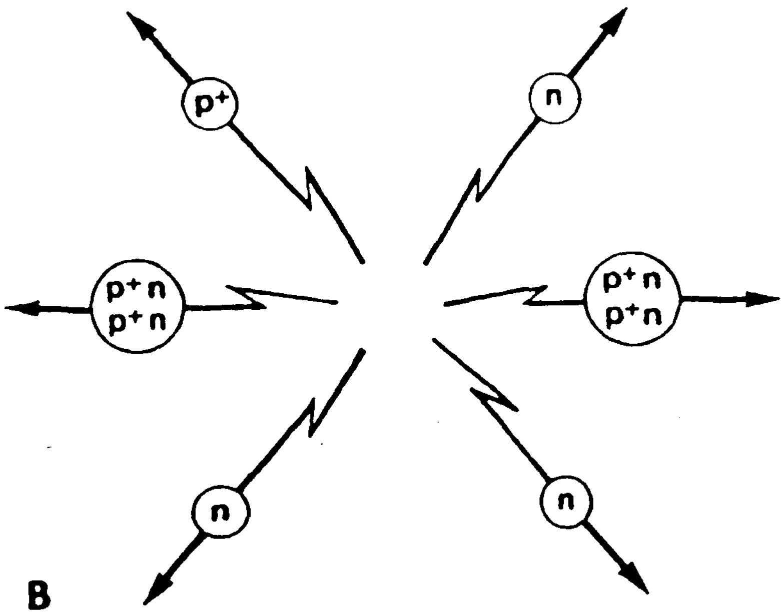


FIG. 15–8. Cross-section of the dose distribution that can be obtained in the treatment of an imaginary carcinoma of the cervix, using a four-field technique with ^{60}Co γ-rays, 11-MeV x-rays from a betatron, and 160-MeV protons from the Harvard cyclotron. (From Koehler AM, Preston WM: Radiology 104:191–195, 1972)

Source: Hall, pg. 313.



A



B

Source: Hall, pg. 24.

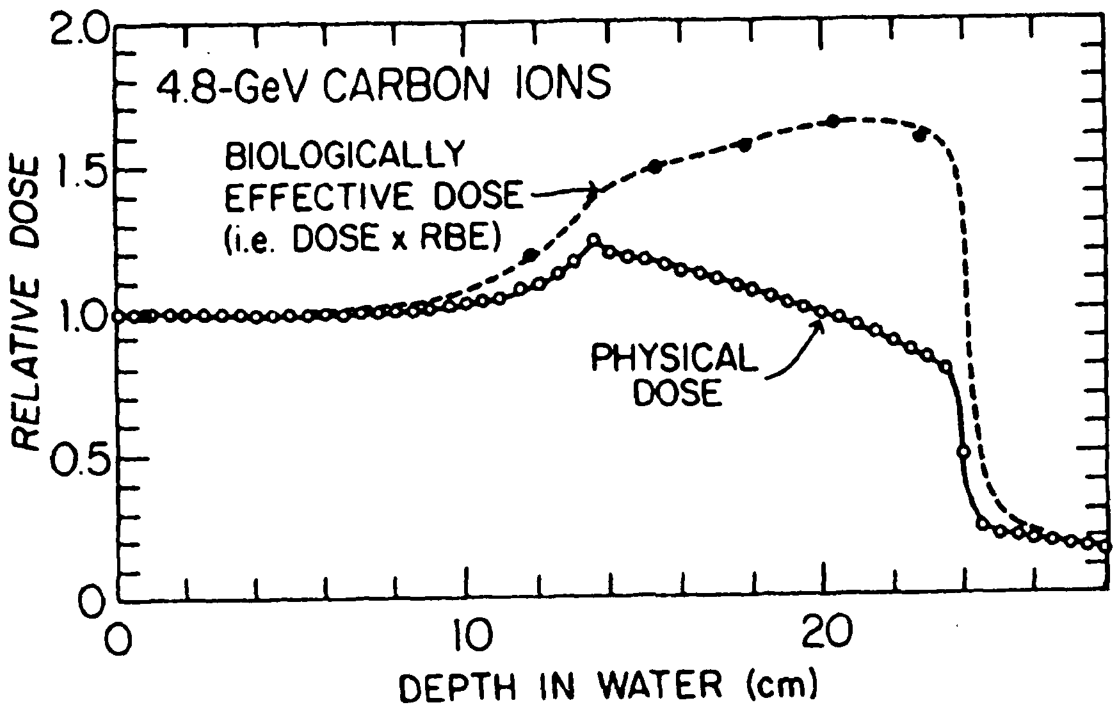


FIG. 15–10. Depth-dose curve for carbon ions in which the Bragg peak has been spread out over 10 cm by the use of a ridge filter. The ions had an initial energy of 400 MeV/nucleon, corresponding to a total energy of 4.8 GeV. The spread-out peak is located between 12 and 22 cm deep. The lower curve represents the physical absorbed dose. The upper curve represents the biologically effective dose; it is, in fact, the product of dose and RBE, calculated at the level of 50% cell survival. (By courtesy of Dr. J.D. Chapman)

Source: Hall, pg. 318.

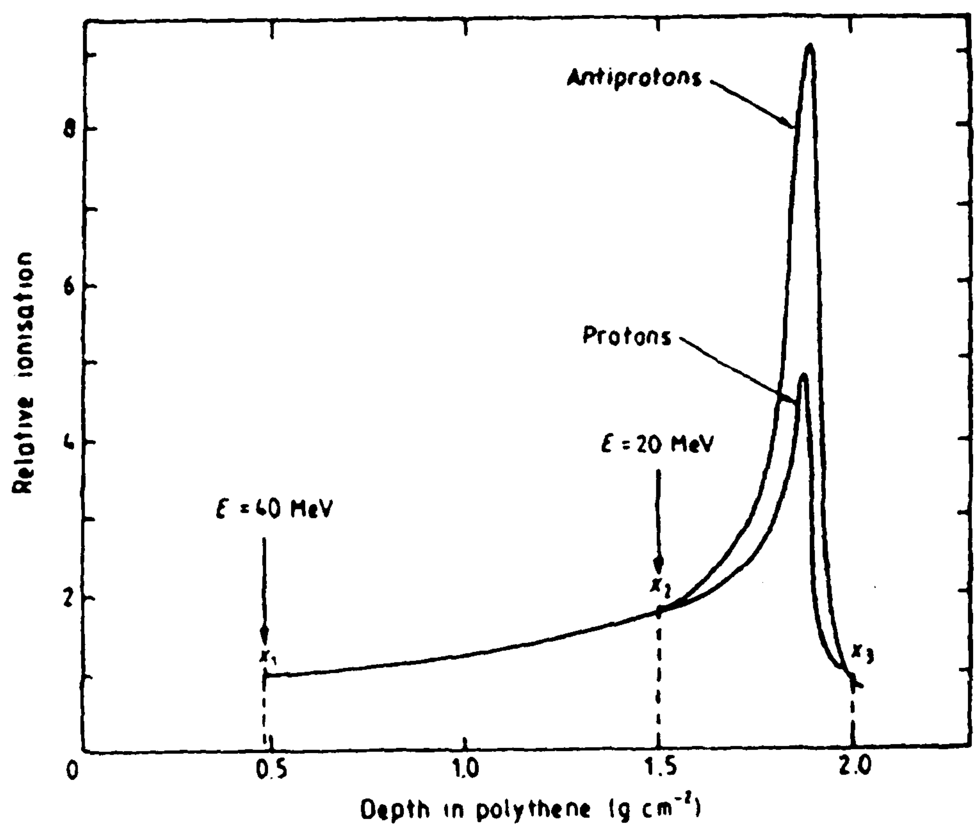
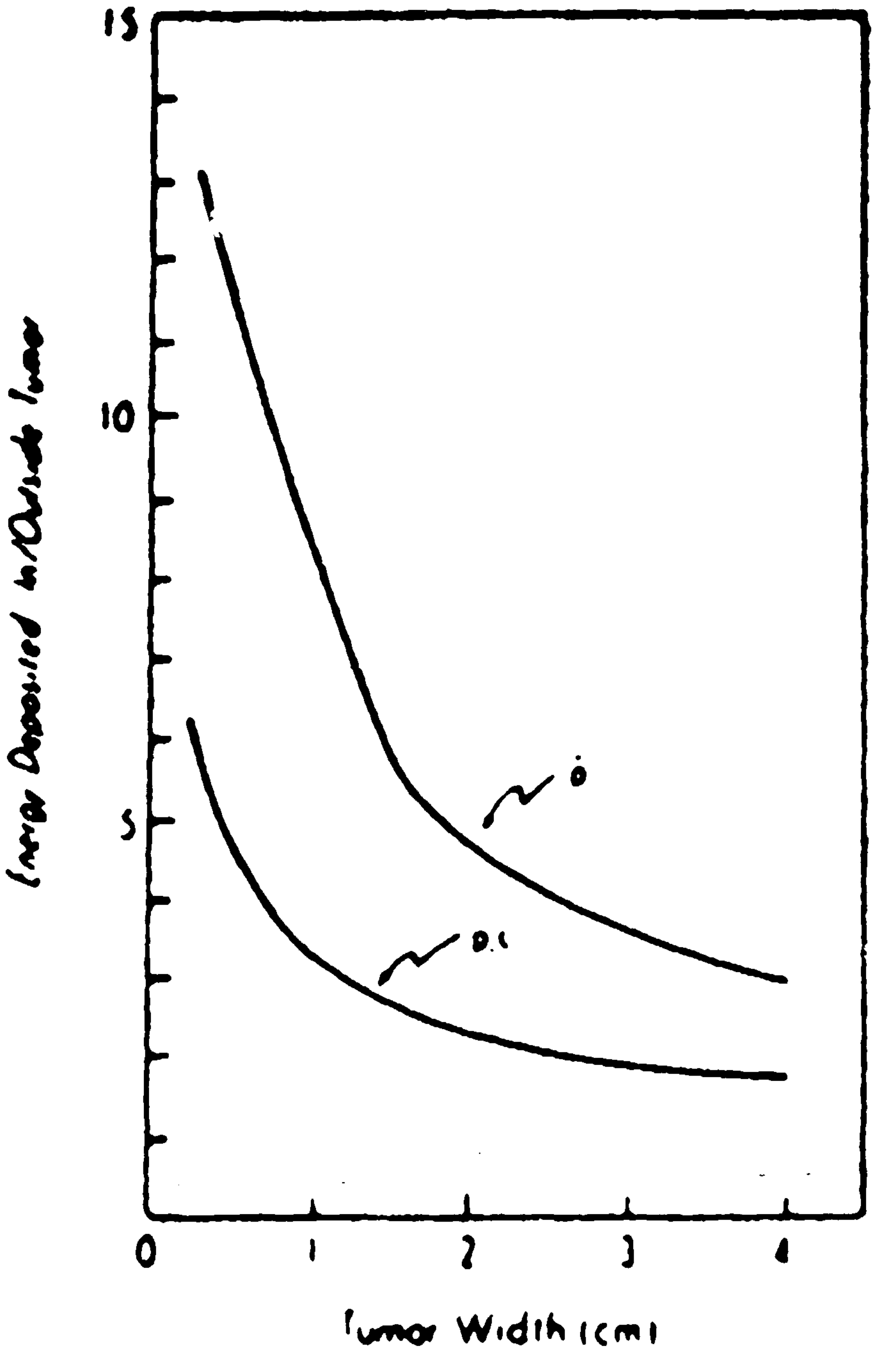
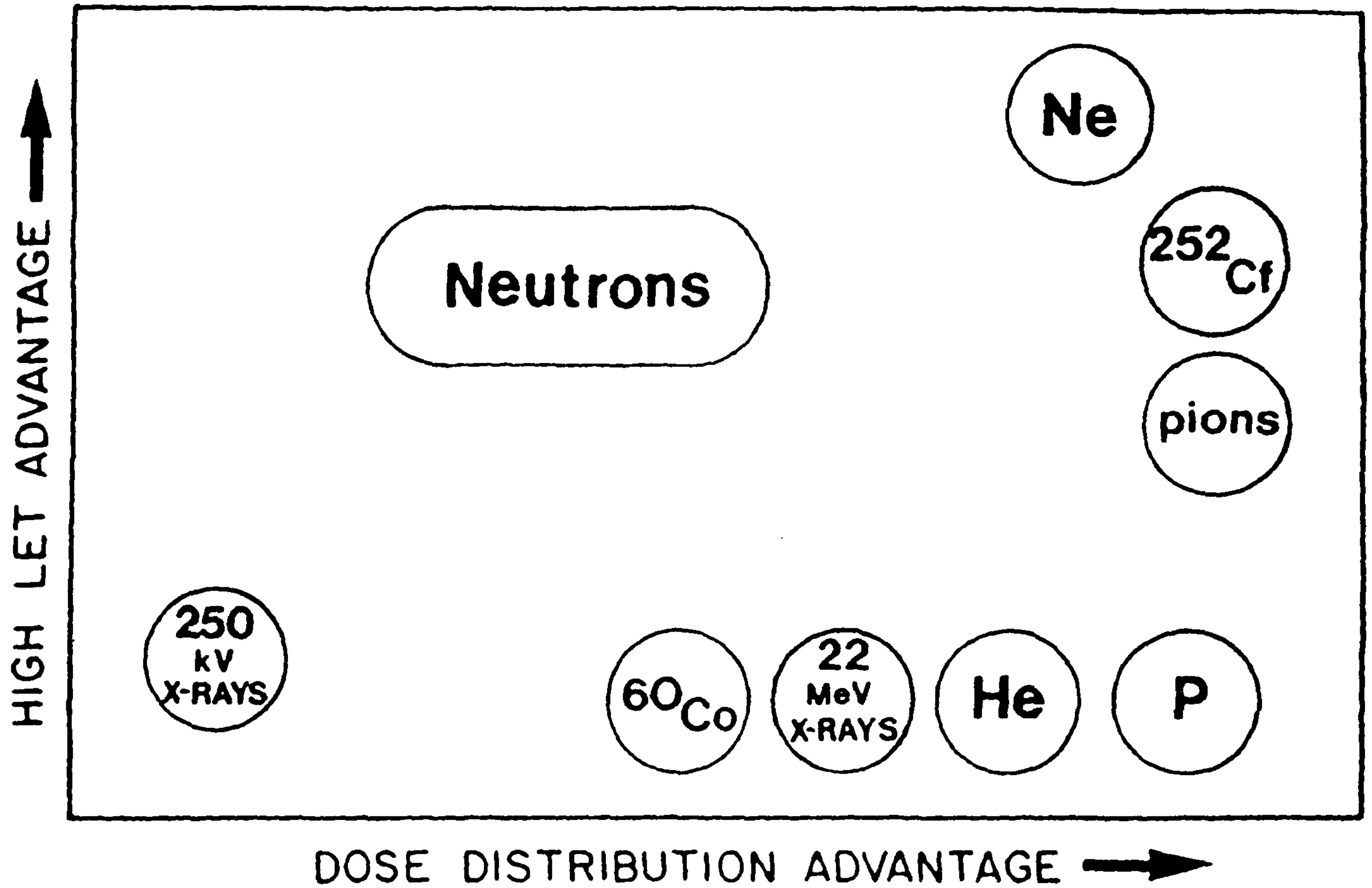


Figure 3. Variation of energy deposition by beams of protons and antiprotons with depth in an absorber. Each curve normalised to 1 at a depth of 0.5 g cm^{-2}.

Source: Sullivan, A. H., "A Measurement of the local energy deposition by antiprotons coming to rest in tissue-like material," Phys. Med. Biol., 1985: 30, 1297-1303.



Source: Gray, L. and Kalogeropoulos, T.E., " Possible Biomedical Applications of Antiproton Beams: Focused Radiation Transfer," Radiation Research, 1984: 97, 246-252.



Source: Hall, pg. 320.

PROSPECTS FOR A COMMERCIAL ANTIPROTON SOURCE

BRIAN VON HERZEN

ANTIMATTER TECHNOLOGY CORPORATION
HILO, HI

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

Prospects for a Commercial Antiproton Source

Brian Von Herzen, Ph.D.

Antimatter
TECHNOLOGY CORPORATION

Objective:

To develop the production facilities, transport systems, and equipment needed to apply antimatter to problems in medicine, aerospace, and academic research.

Antimatter
TECHNOLOGY CORPORATION

Current Efforts

- to obtain complete funding for the production, distribution, and application of antimatter.

- to develop a cost-effective source for antiprotons.

- to develop a portable system capable of storing antiprotons and delivering them to remote sites.

- to develop the necessary imaging, diagnostic and therapeutic equipment for medical applications.

Antimatter
TECHNOLOGY CORPORATION

Funding Being Sought

$195 million for a dedicated production facility, or an extension of an existing facility

$15 million to develop a portable storage device capable of transporting antiprotons to remote sites.

$35 million for medical applications, including imaging, diagnosis, medical clinics, and development.

$245 million needed for commercial break-even

Antimatter
TECHNOLOGY CORPORATION

Possible Antiproton Sources

- Collaboration with Brookhaven
- Collaboration with Fermilab
- Collaboration with a future facility
  - Advanced Hadron Facility at Los Alamos
  - Triumf in Canada
  - SSC Collaboration
- Dedicated production facility

Antimatter
TECHNOLOGY CORPORATION

Transport and Storage Systems

- Medical Tabletop ring by Prof. Robert Wilson
- Design studies in RAND proceedings by researchers at UCLA and Los Alamos
  - Penning traps
  - Superconducting storage rings
- Molecular storage of antimatter

Antimatter
TECHNOLOGY CORPORATION

Imaging and Treatment

- Proton therapy at Harvard Cyclotron, and Mass General Hospital (4500 patients treated).
- Antiprotons are thought to be much more effective than protons, leading to reduced mortality.
- Imaging experiments at BNL (Kalogeropoulos *et al.*)
- Acceptance of particle treatment by the medical community (Loma Linda medical cyclotron installed).

Antimatter
TECHNOLOGY CORPORATION

Potential Markets

- Cancer Treatment
- Medical Imaging
- Non-destructive Testing

Antimatter
TECHNOLOGY CORPORATION

Cancer Treatment

- $40 billion spent per year on cancer treatment
- 1 million new cases of cancer each year
- Over half of the patients receive radiation therapy.
- Antiprotons are the most selective particles in being able to deliver radiation to the tumor while leaving overlying tissues unharmed.
- A ten percent market penetration in the short-term could be expected to produce revenues of over $1 billion per year.

Antimatter
TECHNOLOGY CORPORATION

Medical Imaging Market

- The medical imaging market is even larger than the cancer market ($50 billion).
- CT scans produce too much radiation.
- Magnetic resonance imaging has limitations to certain types of tissue.
- Benefits from combined imaging and therapy.
- No really satisfactory techniques exist for mammography.

Antimatter
TECHNOLOGY CORPORATION

Non-Destructive Evaluation

- Aerospace applications for critical components
  - Turbines
  - Composites
  - Structural members
  - *Inspection of aging aircraft*
- Aerospace spends 2% of sales on non-destructive test
- Aerospace sales amount to over $50 billion per year
- Aerospace NDE is already a billion dollar market
- Electronic Industry
  - Inspection of solder joints
  - Automated annealing of cold solder joints

Antimatter
TECHNOLOGY CORPORATION

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PROSPECTS FOR EXCITING EXTREME STATES IN NUCLEAR MATTER WITH INTENSE ANTIPROTON BEAMS

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HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

EXCITING EXTREME STATES IN NUCLEAR MATTER USING INTENSE ANTIPROTON BEAMS

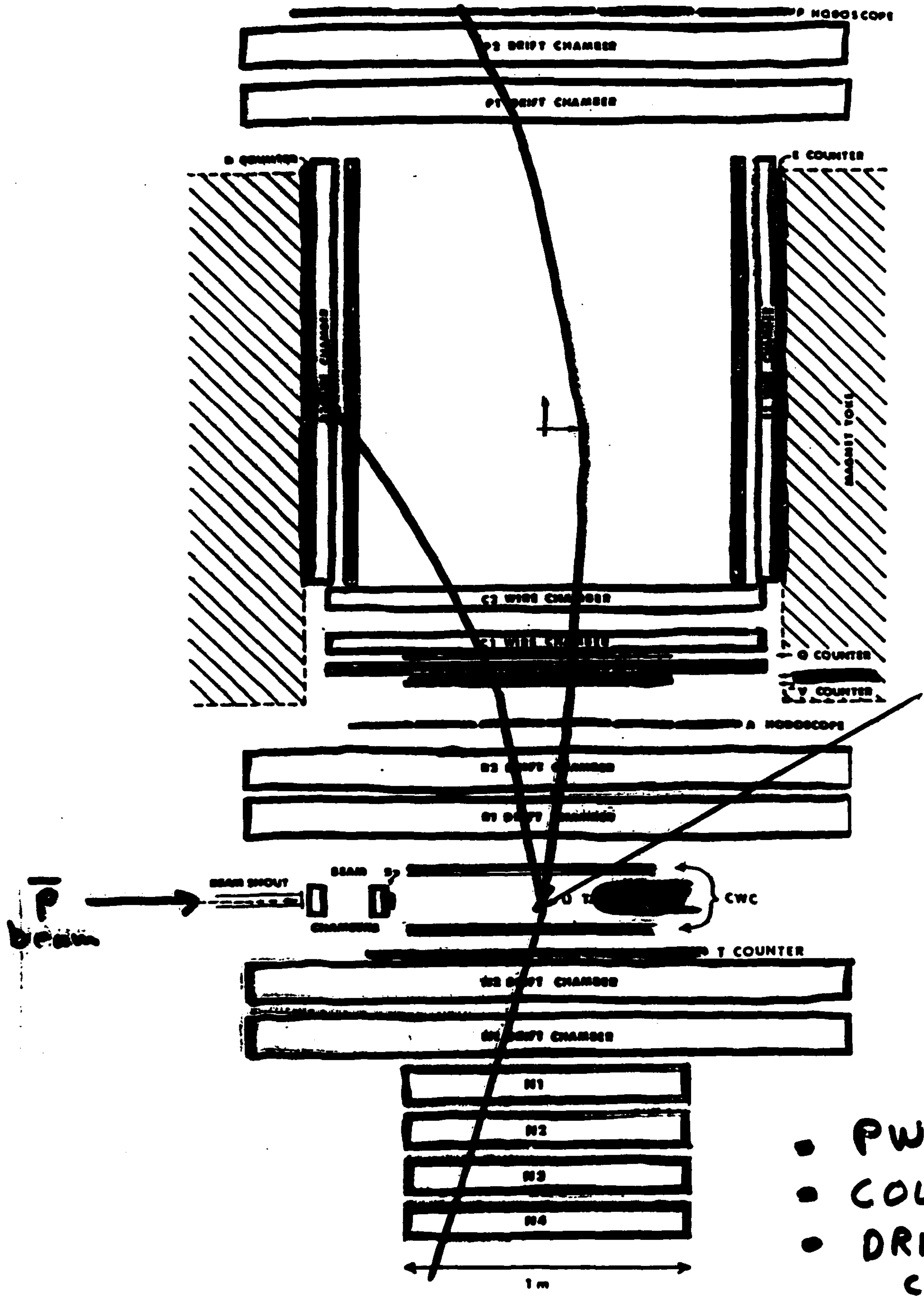
AUTHORS: E.D. Minor
T.A. Armstrong
R. Bishop
V. Harris
R.A. Lewis
G.A. Smith

Pennsylvania State University

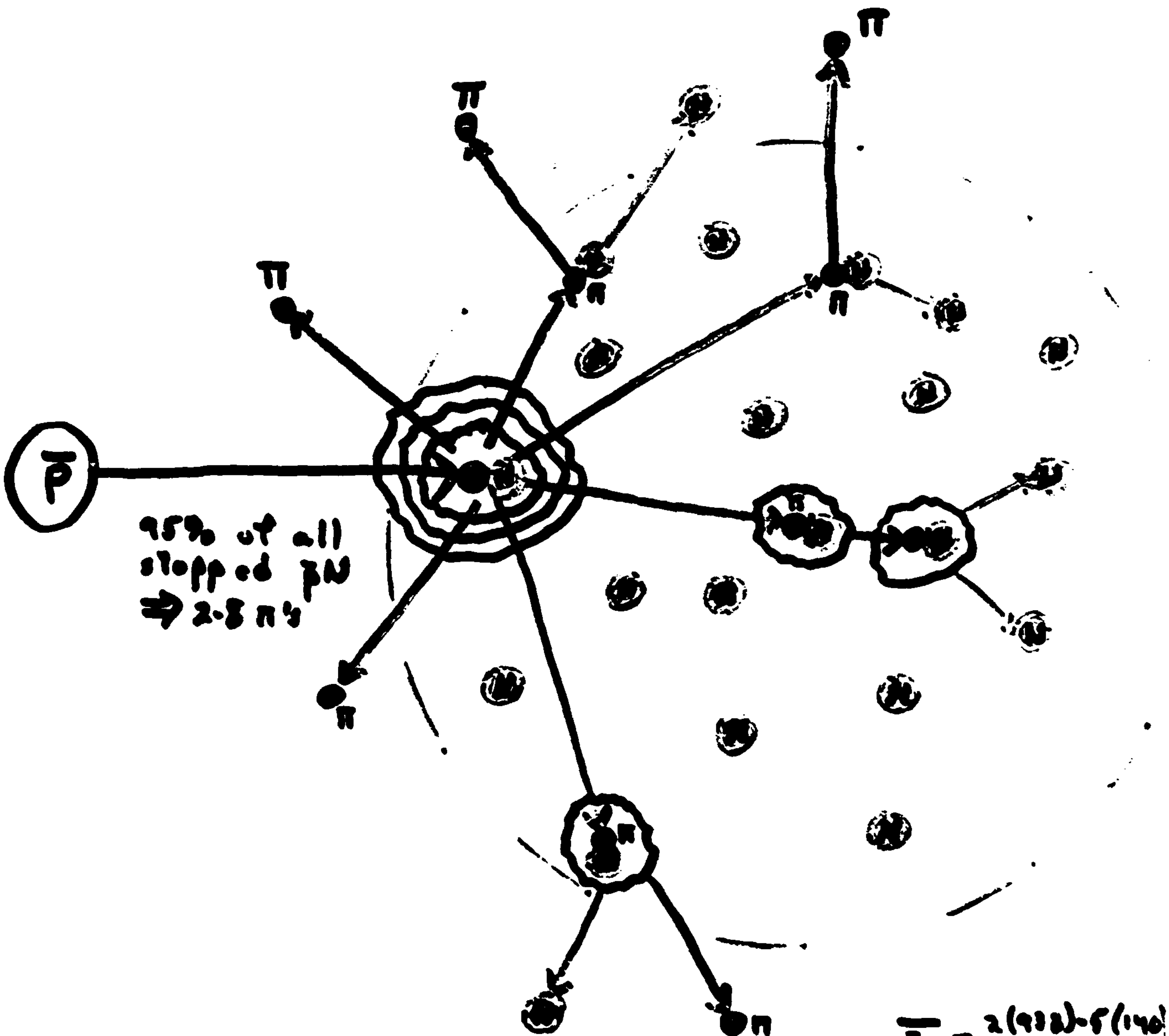
SUPPORTED BY: Air Force Office of Scientific Res.
Air Force Systems Command
USAF grant
U.S. National Science Foundation

WORKSHOP ON ANTIPROTON TECHNOLOGY

MAY 10, 1989
BNL



• PWC's
• COUNTERS
• DRIFT CHAMBERS



$$\bar{E}_n = \frac{2(938)-5(140)}{5}$$
$\simeq 235$ MeV KE

$\sqrt{s} = 1266$ MeV
for πN

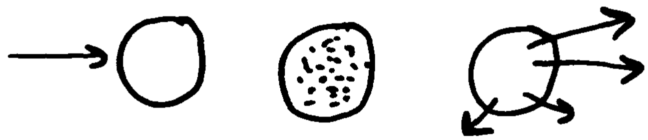
$1032 \le \sqrt{s} \le 1300$
for (3,3)

Binary Annihilation
$\bar{p}$N

J. Cugnon
Maine $\bar{p}p$ '88

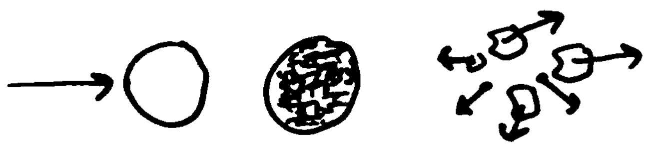
NUCLEAR RESPONSE TO EXCITATION ENERGY E^*?

- if $E^*/A \lesssim 2\text{-}3$ MeV, the nucleus de-excites by thermal evaporation



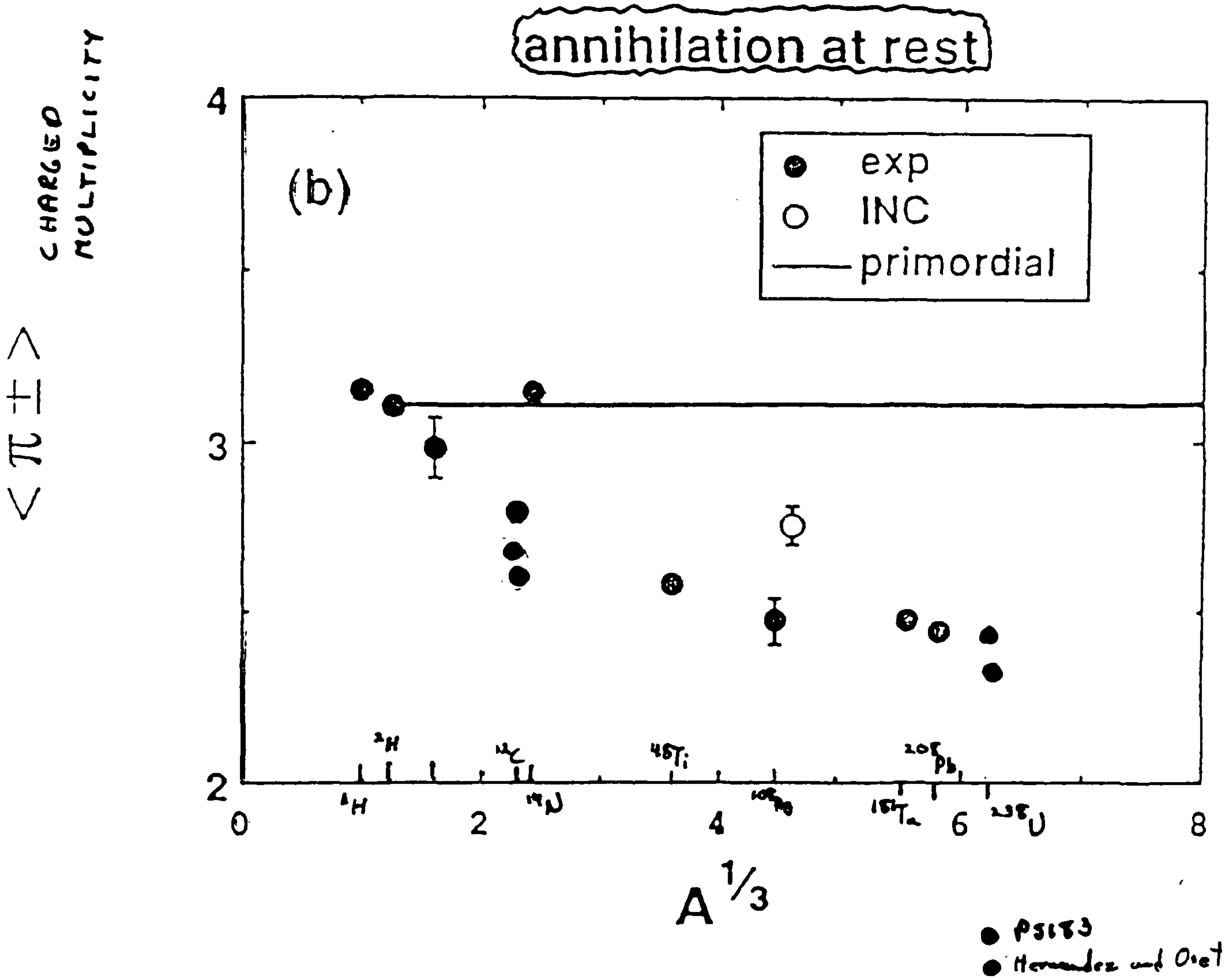
(compound nucleus, N. BOHR)

- if $E^*/A \gtrsim 2\text{-}3$ MeV, the nucleus fragments



(multi fragmentation)

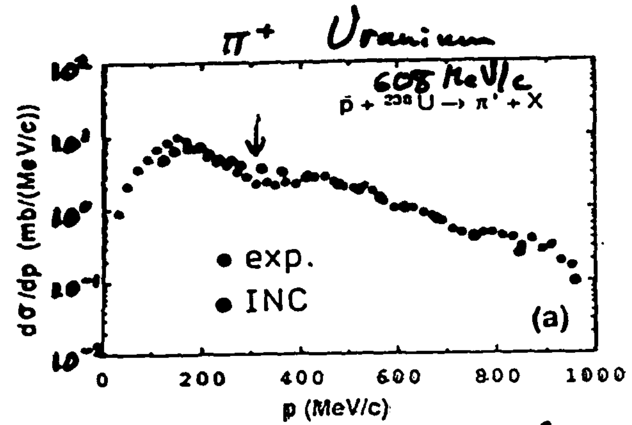
- if $E^*/A \gg 8$ MeV, the nucleus disintegrates
  p, d, t, ...

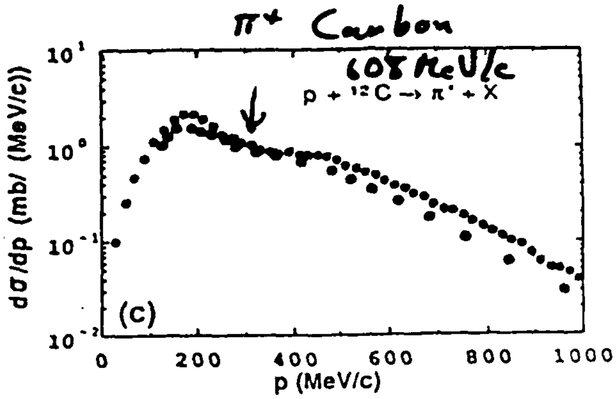


cf: J. Cugnon, P. Deneye, J Vandermeulen, Preprint, Liège.
E. Hernandez, E. Oset. Valencia. Private communication

PS183 { CARBON $\langle N_{\pi^\pm} \rangle = 2.59 \pm 0.04$
URANIUM $\langle N_{\pi^\pm} \rangle = 2.32 \pm 0.02$

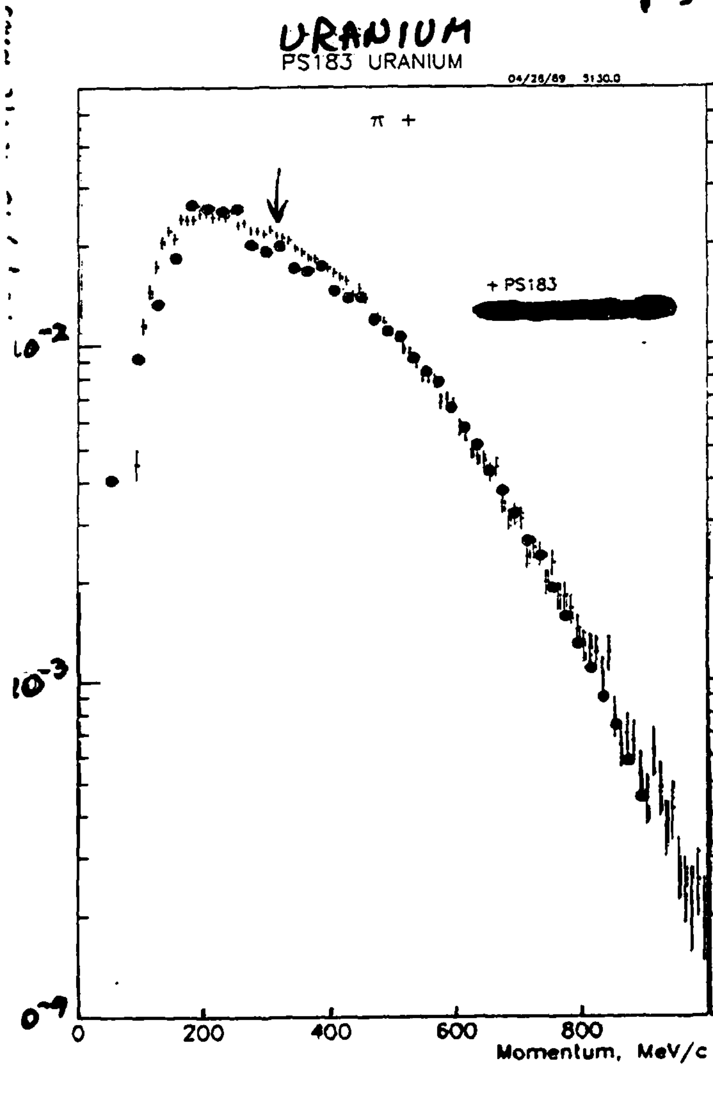
Ref: Exp: P.L. McGaughey et al. Phys. Rev. Lett. 56 (1986) 2156.
INC: J. Cugnon, P. Deneye, J. Vandermeulen. Preprint

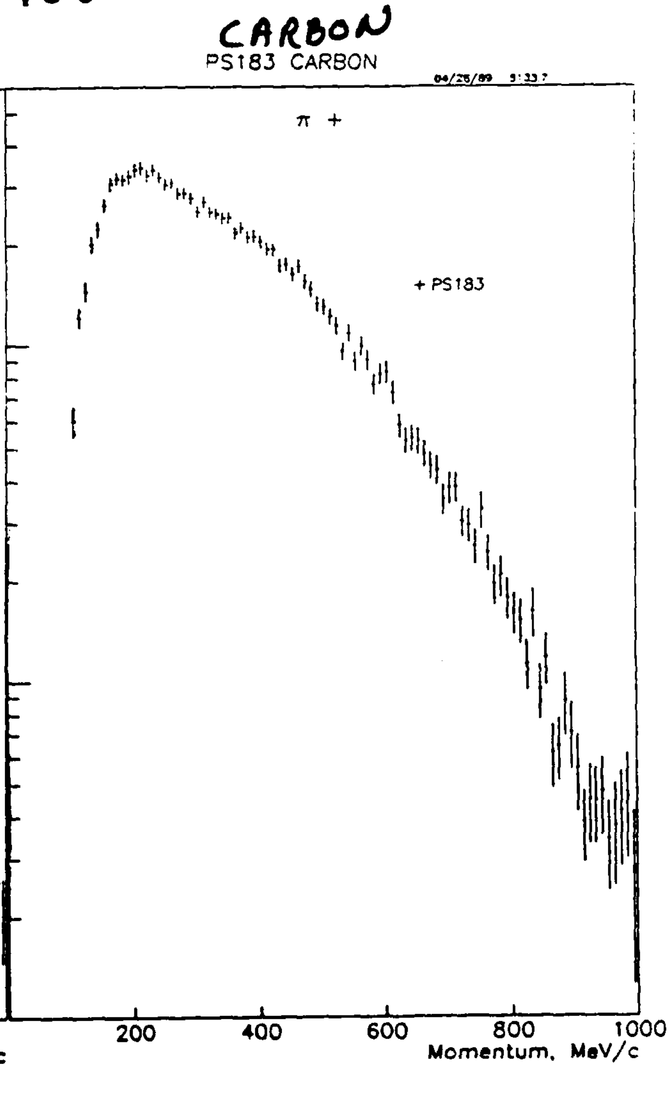




McGaughey et al.

PS 183

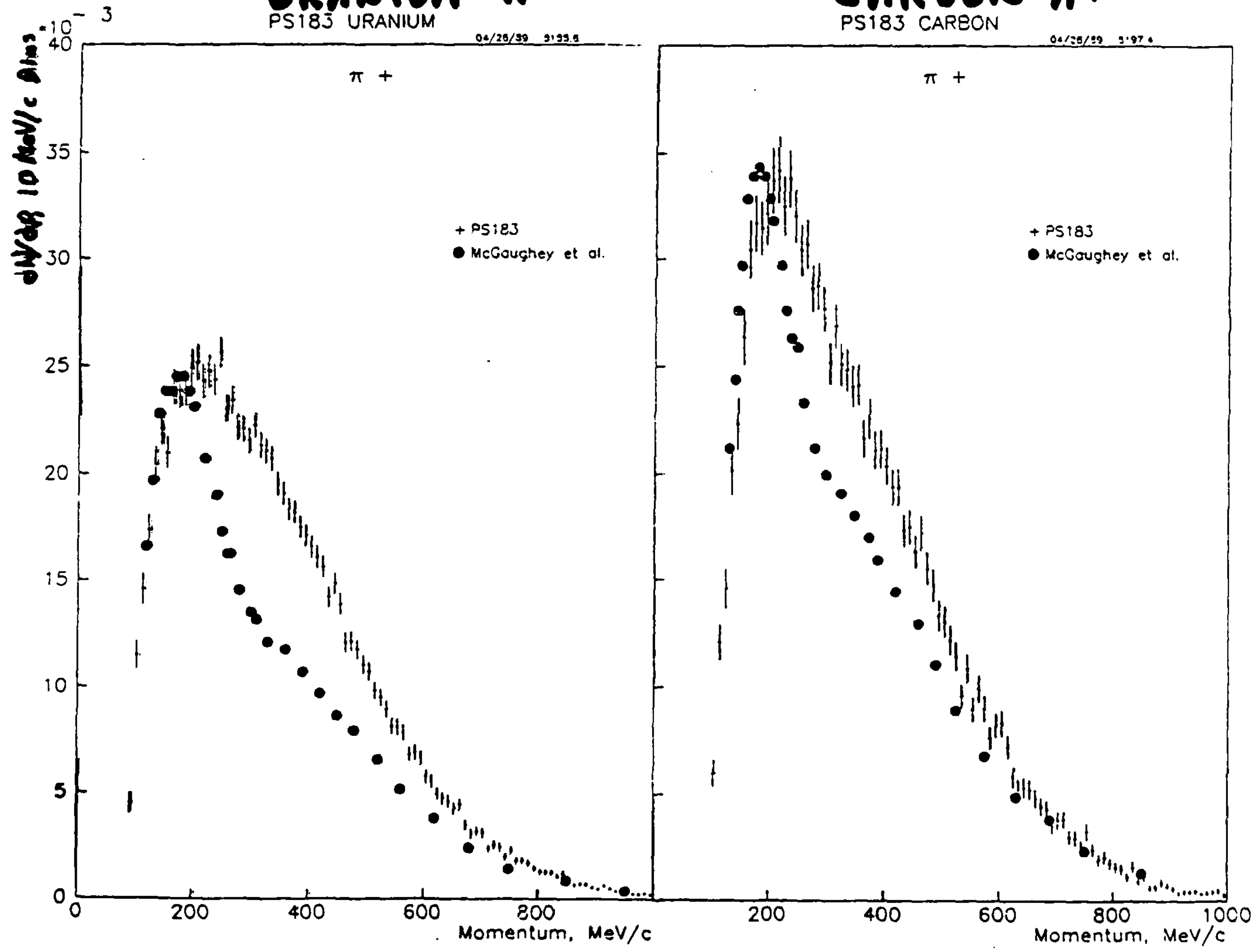




Ref: INC: E. Hernandez, E. Oset. Valencia. Private communication.

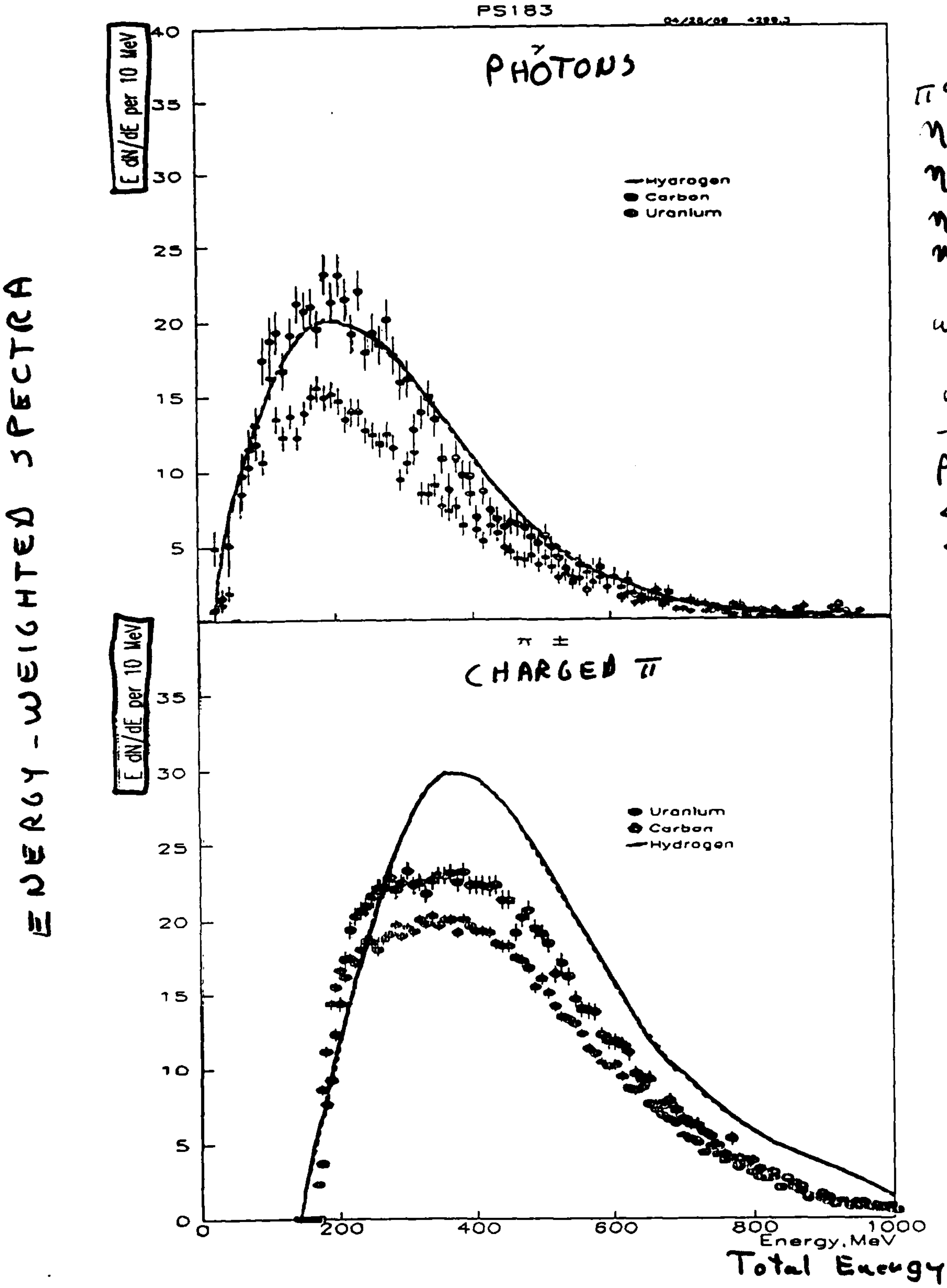
{ PS183 (at rest)
{ McGaughey et al. (608 MeV/c) }

URANIUM π^+ CARBON π^+



Integrated Multiplicities:

		Uranium	Carbon
$\langle N_{\pi^+} \rangle$	stopped $\bar{p}$	0.93	1.12
	608 MeV/c $\bar{p}$	0.69	0.96



$\pi^0 \to 2\gamma$

$\eta \to \gamma\gamma$

$\eta \to 3\pi^0 \to 6\gamma$

$\eta \to \pi^0\gamma\gamma \to 4\gamma$

$\eta \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$

$\omega \to \pi^+\pi^-\pi^0$, $\pi^0 \to \gamma\gamma$

$\omega \to \pi^0\gamma \to 3\gamma$

$p\bar{p}$ production.

$\langle\eta\rangle = 0.07 \pm 0.01$

$\langle\omega\rangle = 0.28 \pm 0.11$

$\langle\pi^\pm\rangle \cong 3.1$

$\langle\pi^0\rangle \cong 1.8$

Refs: Adiels, L. et al. Phys. Lett. 182B (1986) 405.
Roy, J. Proc. of the Fourth Int. Symp. on $N\bar{N}$ Interactions. May 2-4, 1975. Syracuse, N.Y.
J. Cugnon, P. Deneye, J. Vandermeulen. Liège. Preprint

ENERGY TRANSFER

$$E_{TRANS} = 1876.6 - \sum_{i=\{\pi^\pm, \gamma\}} \langle n_i \rangle \langle E_i \rangle$$

	$\langle n_\gamma \rangle$	$\langle E_\gamma \rangle$ MeV	$\langle n_{\pi^\pm} \rangle$	$\langle E_{\pi^\pm} \rangle$ MeV	E_{TOT} MeV	E_{TRAN} MeV
CARBON	3.62 ± 0.22	196 ± 1	2.59 ± 0.03	385 ± 2	1706 ± 45	170 ± 45
URANIUM	2.79 ± 0.18	185 ± 1	2.32 ± 0.02	377 ± 2	1380 ± 34	497 ± 34

COMPARISONS: E_{TRAN}

CARBON: E. Hernandez, E. Oset (Prediction) (n=4) 228 MeV

P. Jasselette et al. (Prediction) OXYGEN 260 MeV

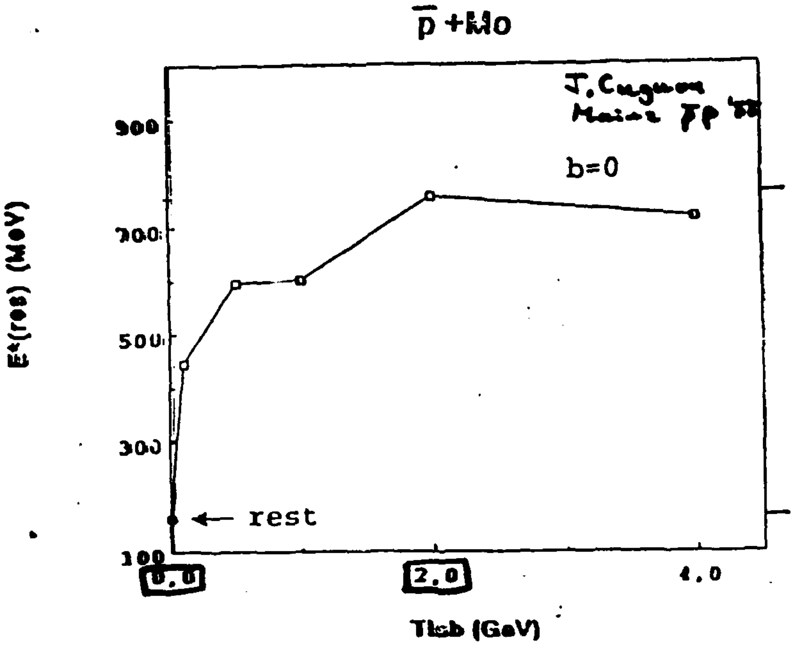
URANIUM: E. Hernandez E. Oset (Pred) 491 MeV

P. Jasselette et al. (Pred) 380 MeV

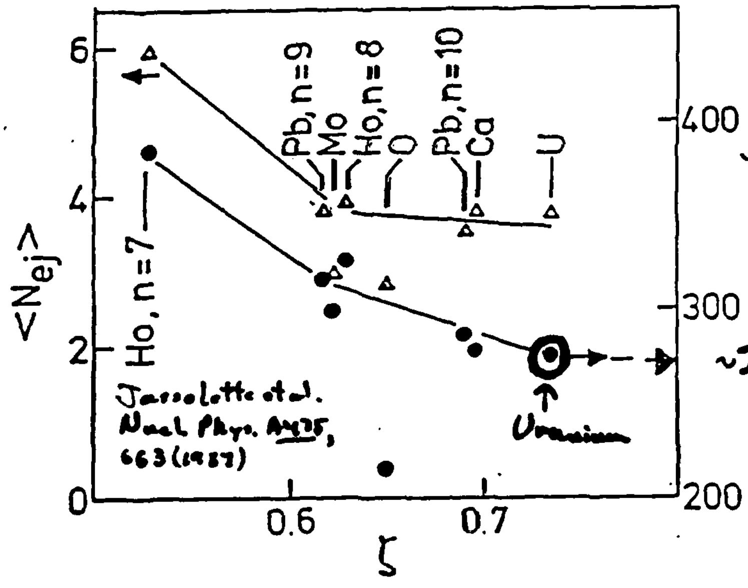
E^*/A	Future Behavior
$\leq$ 2-3 MeV	thermal evaporation
$\gtrsim$ 2-3 MeV	multifragmentation
>> 8 MeV	nuclear disintegration : p, d, t, ...

Refs: Armstrong, T.A., et al. Zeit. f. Phys. A332 (1989).
E. Hernandez and E. Oset. Valencia, Private communication
Jasselette, P., et. al. Nucl. Phys. A484 (1988) 542.

EXCITATION ENERGY E^*



E^* scales by a factor of 5 between $\bar{p}$ annihilation at rest and $\bar{p}$ at 2.0 GeV



~230 MeV = Total ejectile K.E.

$\bar{p}$ - Uranium annihilation

$E^* = 1876.6 - E_{\pi} - W_{EJ} = 226$ MeV (at rest)

Subcritical

But, at 2 GeV: $E^* = 5 \times E^*(\text{rest}) = 1{,}133$ MeV

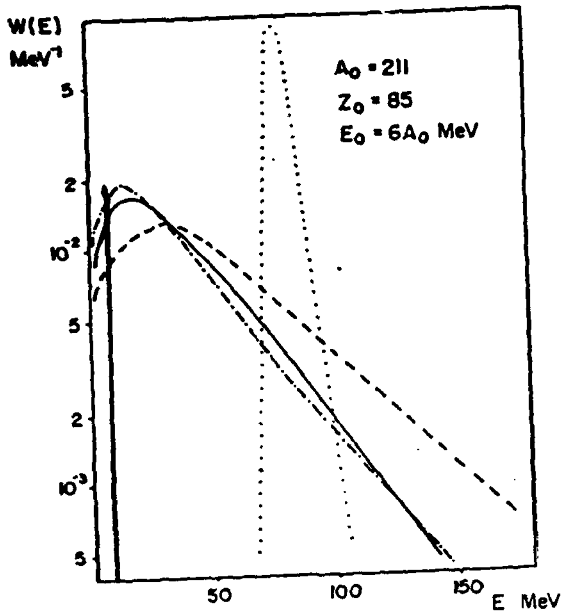
$\boxed{E^*/A = 4.76 \text{ MeV}}$

! Multifragmentation!

WHAT'S THE POINT?

ENERGY DISTR. (A≈27 FRAGS)

A.S. Botvina et al. / Statistical simulation



Botvina, A.S. et al. Nucl. Phys. A475 (1987) 663

Nucleus	$^{27}Al_{13}$	$^{184}W_{74}$	
Fragment	^{14}N	$^{27}Al_{13}$	
Range (TARG THICKNESS), T	10^4 Å	0.5×10^4 Å ←	The Stopping Power and Range of Ions in Solids, J.F. Ziegler, J.P. Biersack, U. Littmark, Pergamon, New York, 1985.
Cross Section, σ	0.36 b	1.3 b	$\frac{\sigma\cdot\beta}{A^{2/3}} \approx 40$ mb
Mean free path, λ	46 cm.	1.2 cm.	$\lambda = \left(\sigma \frac{N_0}{A}\rho\right)^{-1}$
Yield	2.2 per 10^6 $\bar{p}$'s	4.2 per 10^6 $\bar{p}$'s	$Y = \frac{T}{\lambda} R_{\bar{p}}$

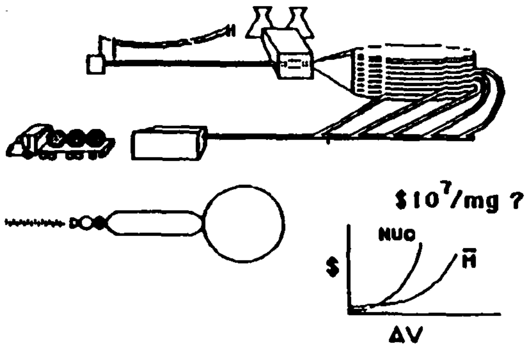
STATUS OF ASTRONAUTICS LABORATORY STUDIES RELATING TO CONDENSED ANTIMATTER

GERALD NORDLEY

APPLIED RESEARCH IN ENERGY STORAGE OFFICE
ASTRONAUTICS LABORATORY (AFSC)
EDWARDS AFB, CA

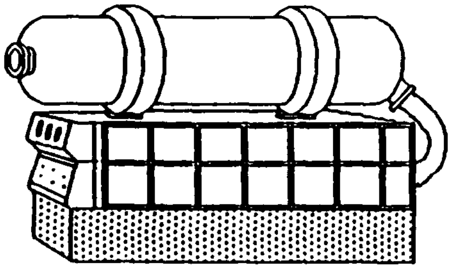
PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

ANTIMATTER PROGRAM AREAS



ANTIPROTON PRODUCTION

OVERVIEW

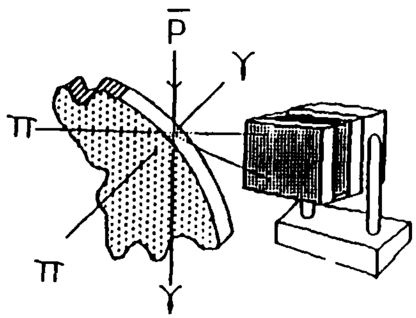


ANTIMATTER STORAGE

OVERVIEW

HYDROGEN CLUSTER IONS

SOLID ANTIHYDROGEN STORAGE



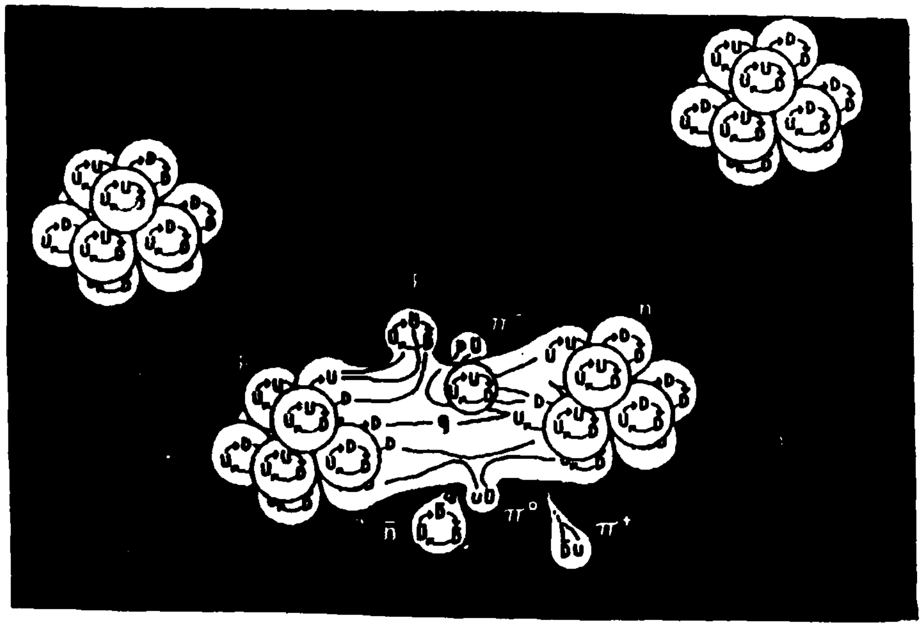
ANTIMATTER ANNIHILATION

OVERVIEW

FUTURE DEVELOPMENT

ANTIPROTON PRODUCTION

MOTIVATION



- O U S SOURCE FOR U S EXPERIMENTS
  - NATIONAL SCIENCE AND TECHNOLOGY BASE
  - CERN BUSY, UNEASY ON DEFENSE WORK
  - ENABLING FOR DEFENSE RELATED USES

- O EVALUATE FEASIBILITY OF SCALE-UP
  - ENABLING FOR FORECAST II PROPULSION
    - GOAL OF $1M/mg
    - NO OTHER KNOWN "CUSTOMER"

ANTIMATTER STORAGE

MOTIVATION

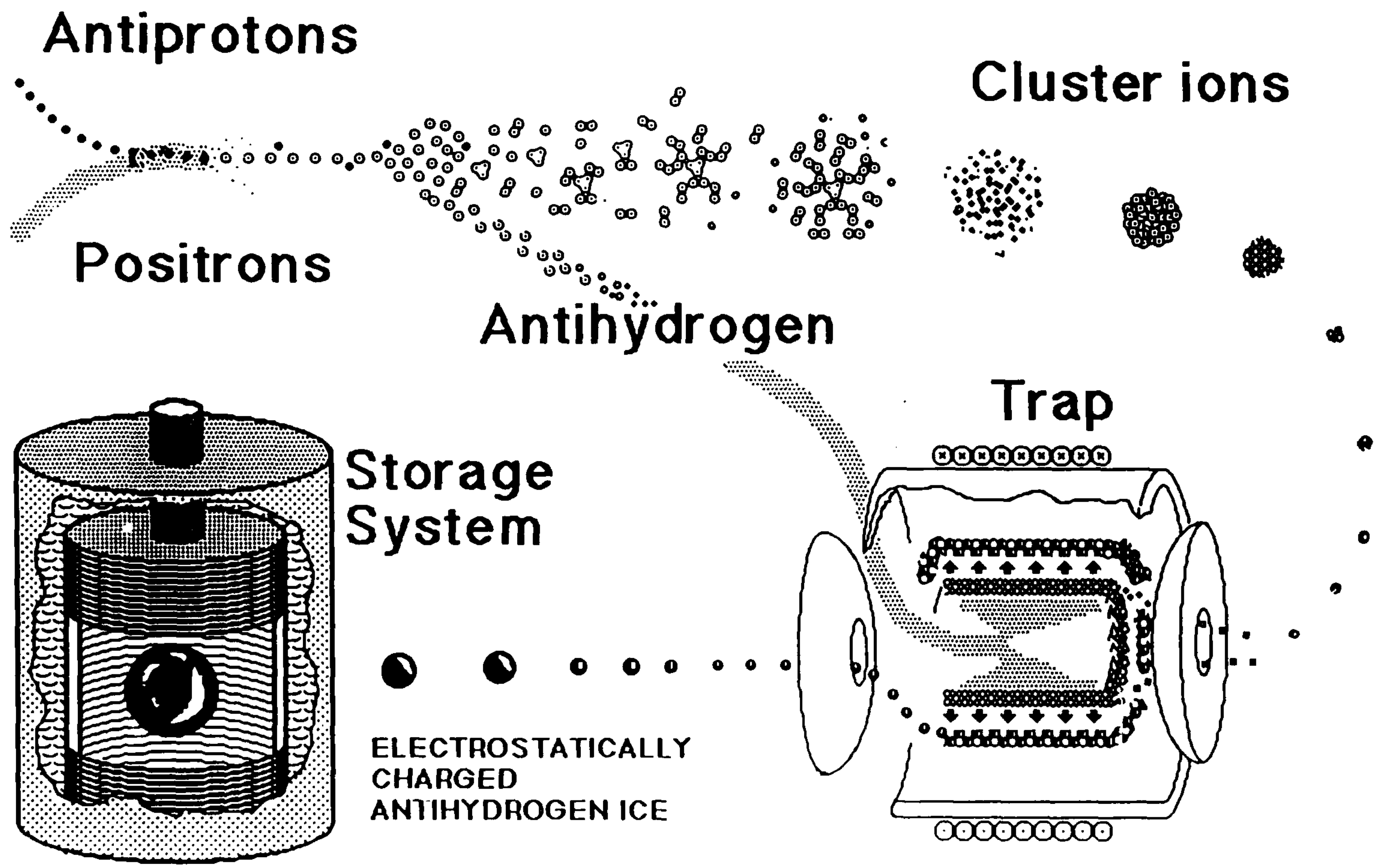
O DEVELOP PORTABLE ANTIPROTON STORAGE
- ENABLE REMOTE EXPERIMENTS
- ESTABLISH TECHNOLOGY BASE
- FACILITATE NEAR TERM USES

O UNDERSTAND CLUSTER ION SCIENCE
- PROPELLANT MOLECULE GROWTH
- CONTACT-FREE NUCLEATION
- CLUSTER TO SOLID TRANSITION ENERGY

O HIGH DENSITY ANTIHYDROGEN STORAGE
- TECHNOLOGICAL SPINOFF
- ENABLING FOR FORECAST II PROPULSION

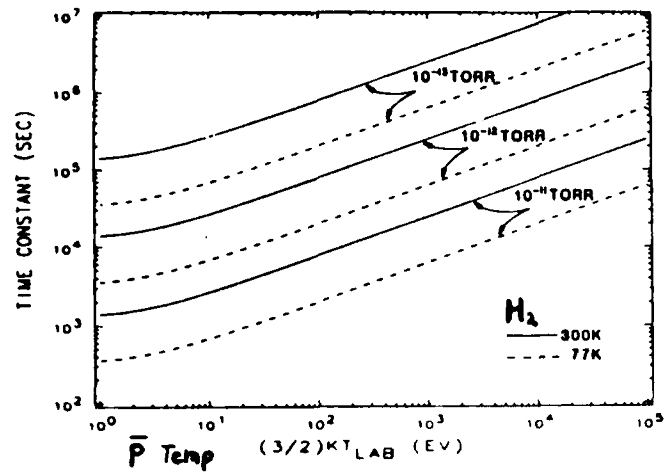
AIR FORCE ANTIMATTER APPLICATIONS

Antihydrogen Energy Storage



7-4-17-5 D33

Contact–Free Storage....

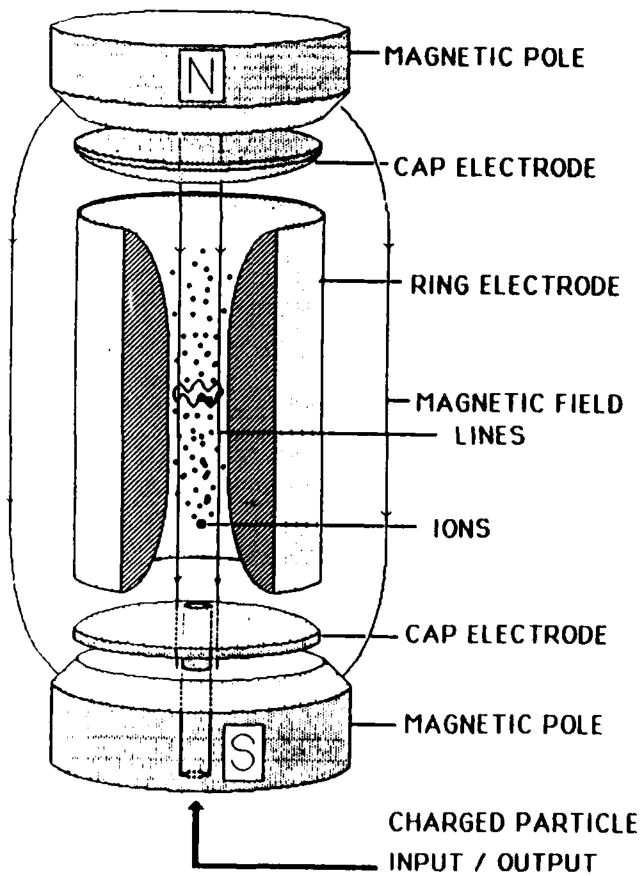


PAYOFF:

- Effective Storage
- Portable
- Enables Near Term Uses
  - NDE of Nozzles, Fuels, Propulsion Materials
  - High Energy Physics at Universities
  - Medical Research

PENNING TRAP

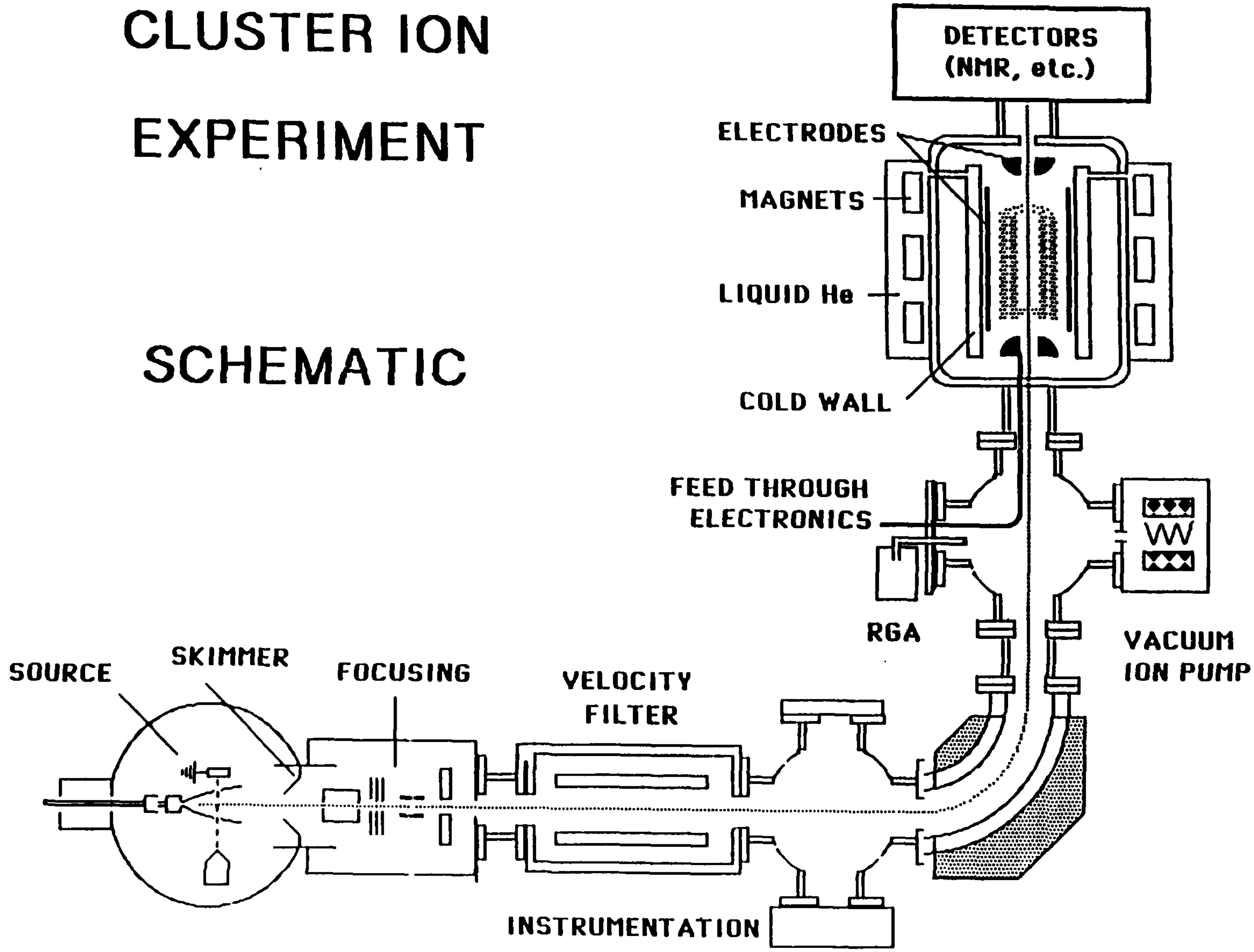
ION TRAPS: PENNING TRAP



TR538a

CLUSTER ION EXPERIMENT

SCHEMATIC



HYDROGEN CLUSTER ION PROJECT   AFAL/AFOSR

SCIENTIFIC OBJECTIVE

- o Determine Associative and Dissociative Pathways for Trapped Cluster Ions
  - Initially, develop technique to follow reaction pathways for H_5^+ systems using a dense non-neutral plasma as a "pseudo-wall" to absorb the energy of association:

$$M^+ + H_3^+ + H_2 \Rightarrow H_5^+ + M^{*+}$$

$$M^+ + H_5^+ + H_2 \Rightarrow H_7^+ + M^{*+}$$

  - Larger H_n^+ systems as experience is gained

- o Assess Potential of Bulk Antihydrogen Nucleation via Cluster Ions

APPROACH

1. Fill the trap with cluster ions of a selected size
2. Introduce molecular hydrogen, allowing it to interact with the trapped ions
   - use proven electromagnetic cooling techniques to maintain temperature
3. Measure size and radial distribution of products through NMR and/or mass spec

PAYOFF/POTENTIAL APPLICATIONS

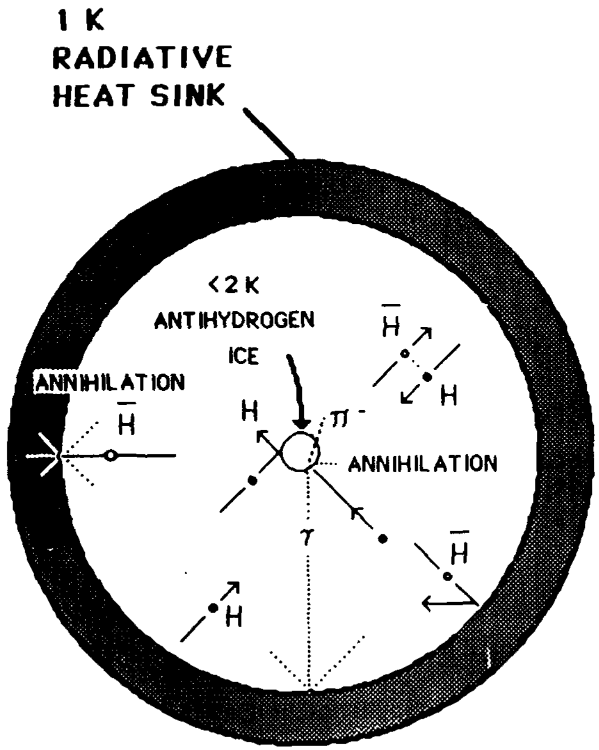
- Bridge between theory and experiment on cluster ion formation & growth
  - Explain semi-empirical models for free expansion nozzles
  - Create new models for contact free processes

- Illuminate third body cooling processes in non neutral plasmas (pseudo walls)

- Provides versatile experimental apparatus in an active field
  - Cluster Ion Beam Experiments (Y.T. Lee et al., UCB)
  - Models for anti-cluster ion nucleation and growth (Saxon, SRI; Turner, AFIT)
  - Contribute to understanding cluster ion formation and deposition processes relevant to ion-matrix HEDM systems (Bae and Cosby, SRI)
  - Related to surface impact studies (Friedman, BNL and others)

- Explore measurement techniques in ion trap environment

ANTIHYDROGEN ICE STORAGE



U. HAWAII (DR JIM GAINES)
BROOKHAVEN NL (DR JIM POWELL)

- Preliminary results

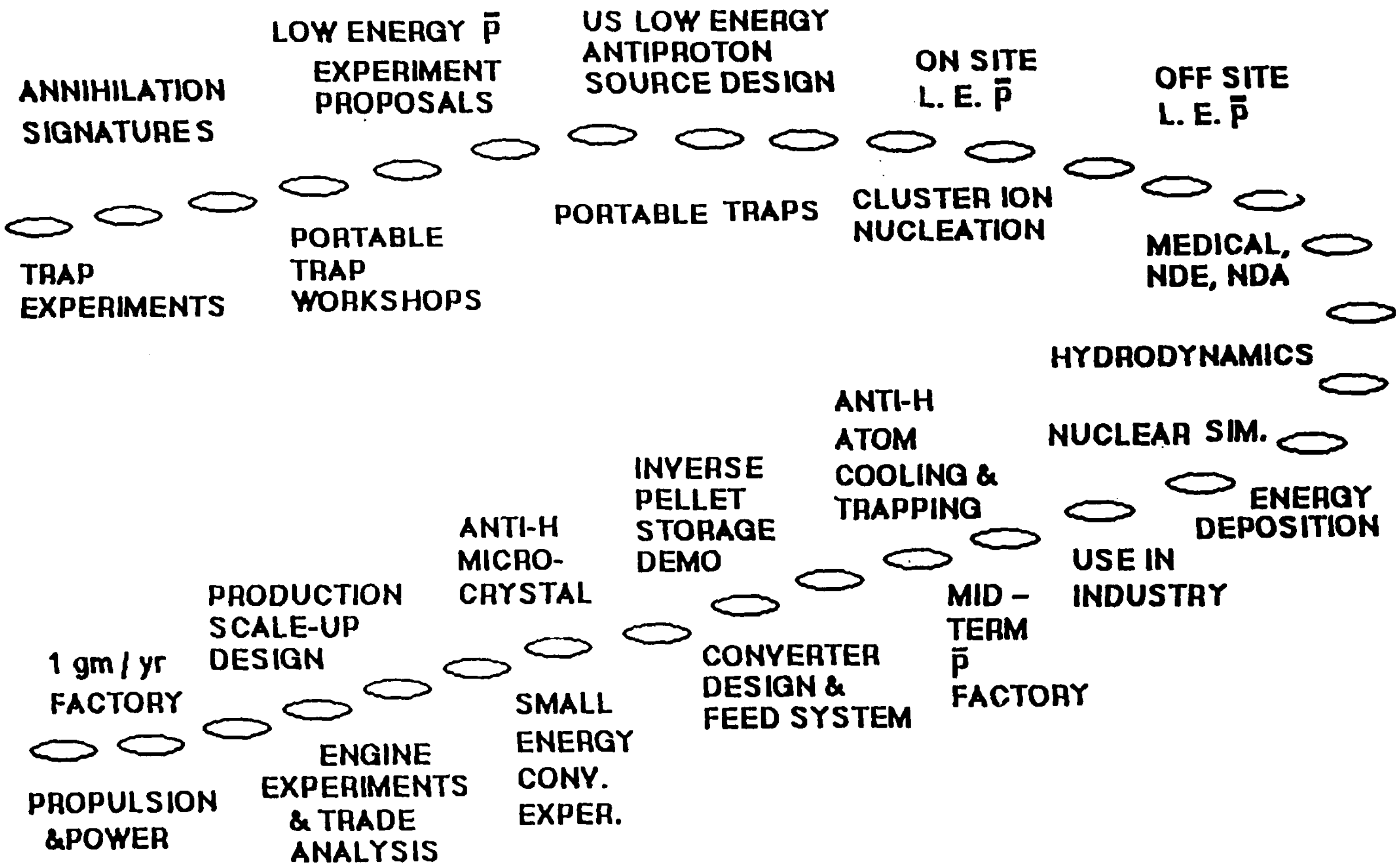
- HOW STABLE IS SOLID ANTIHYDROGEN EXPOSED TO ANNIHILATION REACTION ?
  - 10 mg iceball will withstand 300 Annihilations/s

- WHAT TYPE OF VACUUM DOES THIS IMPLY ?
  - Number density Similar to Interstellar Space
    Based on: 100m/s atom velocity
    100% cross section
    Classical law

- WHAT ELSE DO WE NEED TO KNOW ?
  - Real cross sections
  - Very high Vacuum Material Behavior
  - Synergistic effects

AIR FORCE ANTIPROTON TECHNOLOGY

Path of Antiproton Technology Development



Antimatter Publications 1988 - Supported at Least in Part by AFAL

- General

(1) B. Augenstein, B. Bonner, F. Mills, and M. Nieto, ed., Antiproton Science and Technology, World Scientific, New Jersey, 1988

(2) Nordley, G., "Air Force Antimatter Technology Program" in Proceedings of the INEL Workshop on Intense Positron Beams, Kells and Ottenwhite, ed., World Scientific, New Jersey, 1988

(3)* Forward, R.L. and Davis, J., "Mirror Matter", Wiley Scientific, New York, 1988

- Antiproton Production

(4) Takahasi, Hiroshi, and Werner, Klaus, "Antiproton and Antineutron Production by Relativistic Heavy Ion Collision", BNL technical note (Journal article in preparation)

- Antiproton Storage

(5)* Talbi, D. and Saxon, R., "Theoretical Study of Excited Singlet States of H_3^+: Potential Surfaces and Transition Moments", submitted to J. Chem. Phys. in February 1988

(6) Bahns, J.T., "Condensation and Storage of Hydrogen Cluster Ions", UDRI Technical Report, April 1988

- Antiproton Annihilation and Applications

(7)* Nordley, G., "Application of Antimatter Electric Power to Interstellar Propulsion", submitted to JBIS July 1988, preprint available from AFAL

* Formally reviewed publications

ELECTROMAGNETIC TRAPS

FOR

ATOMIC HYDROGEN OR ANTIHYDROGEN

ISAAC F SILVERA

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HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

Electromagnetic Traps for Atomic Antihydrogen (or Hydrogen)

Isaac F Silvera
Dept of Physics
Harvard University
Cambridge Ma 02138

Three types of traps:

1. Static Magnetic Trap

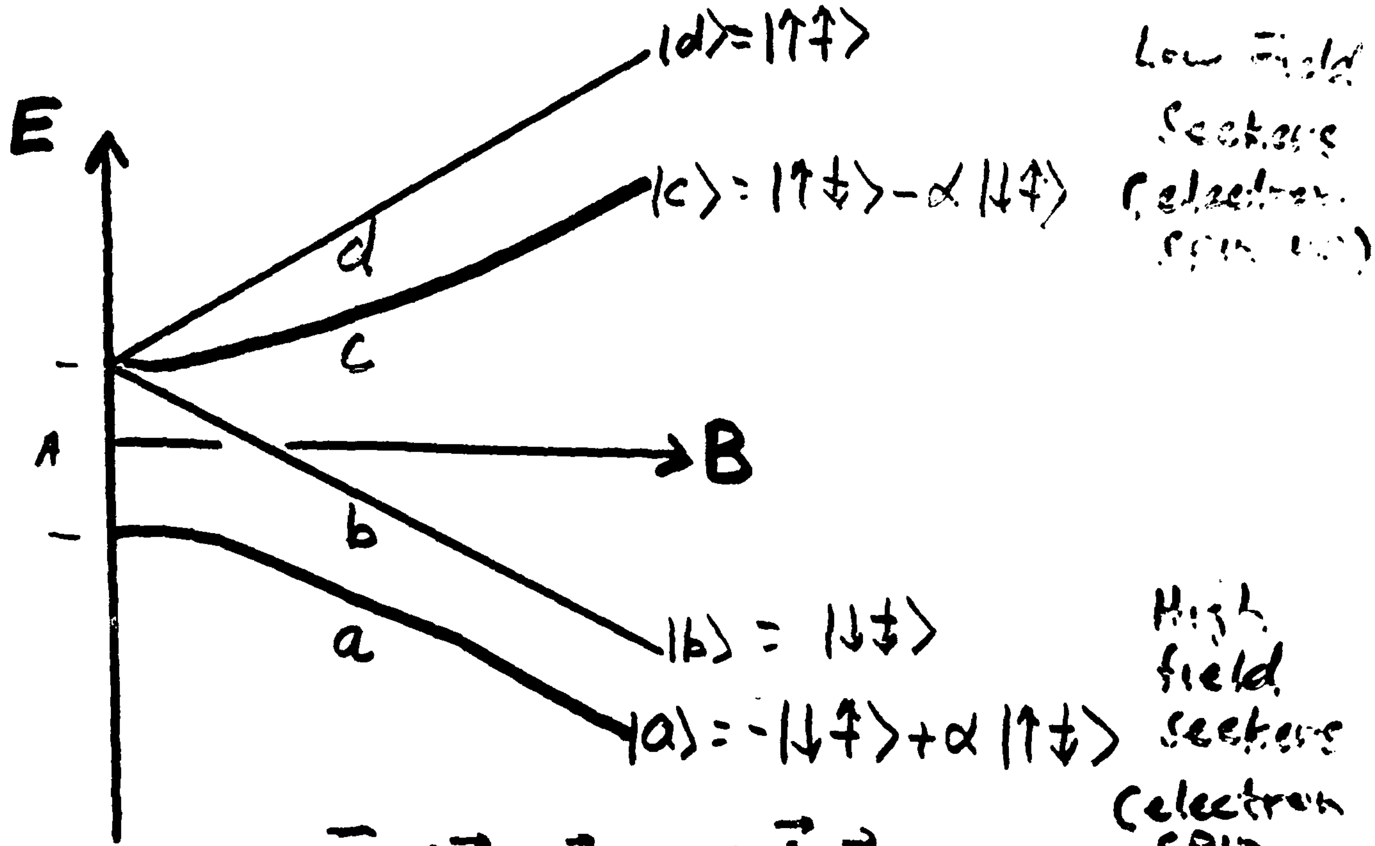
2. Laser Trap

3. Microwave Trap

I shall discuss hydrogen as the problems are the same for antihydrogen

Hyperfine States of Hydrogen

$|m_s\, m_i\rangle$



$$\mathcal{H} = -\vec{B}\cdot(\vec{\mu}_e + \vec{\mu}_p) + A\,\vec{i}\cdot\vec{S}$$

electron spin $= 1/2\,\hbar : \vec{S}$

nuclear spin $= 1/2\,\hbar : \vec{i}$

Total spin : $F = i + s = 1$ or 0

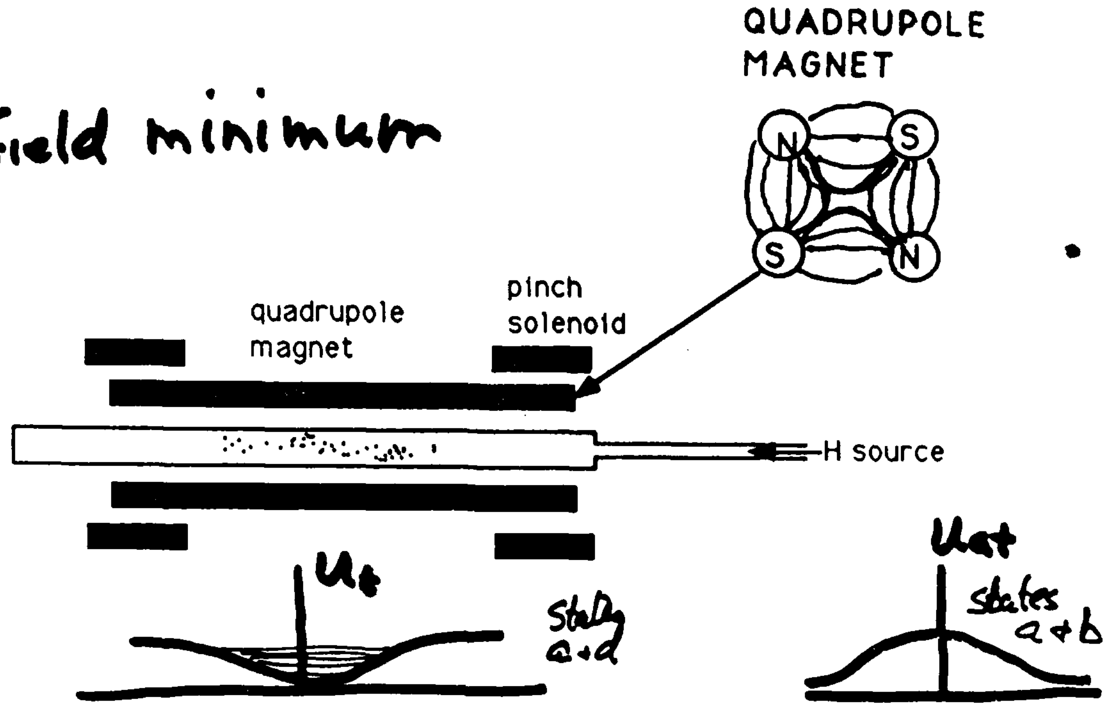
For static magnetic fields
Maxwell's equations do
not allow a field maximum
in Free space.

A Field Minimum is allowed

No restriction on AC fields
(microwave or laser)

STATIC MAGNETIC TRAP (H. Hess)

uses field minimum



Trap potential $U \gg kT$

← Trapped states

relaxation : magnetic dipole
spin-exchange

$\frac{dn}{dt} = -Gn^2$ Rates are very rapid

But $n = 10^{14}/cm^3$ $\tau_{1/2} = 1 sec$

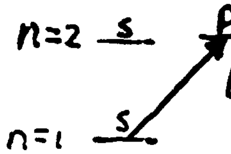
$\frac{1}{n} - \frac{1}{n_0} = -\frac{t}{\tau_{1/2}}$

$\tau_{1/2} = 1/G$

MIT (Kleppner + Greytak et al)
Amsterdam (Walraven et al)

Trap ~ 10^{10}–10^{11} atom
Densities 10^{12} - 10^{13}/cm^3

Laser cooling of hydrogen



Lyman-alpha at 1216 Å

Laser light can cool and trap (Phillips et al; Chu et al; Pritchard) ENS group)

Cool to quantum limit $T_{min} = \frac{\Gamma}{2} = 2.2\,mK$ Lyman-α

$\Gamma \equiv$ spontaneous emission rate

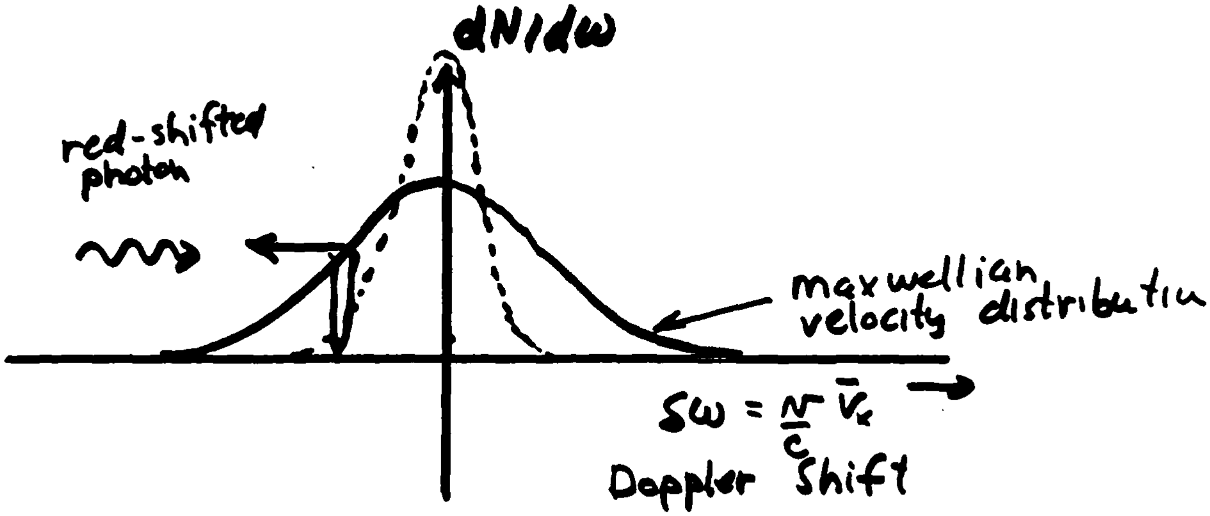
Dipole Trap Potential U

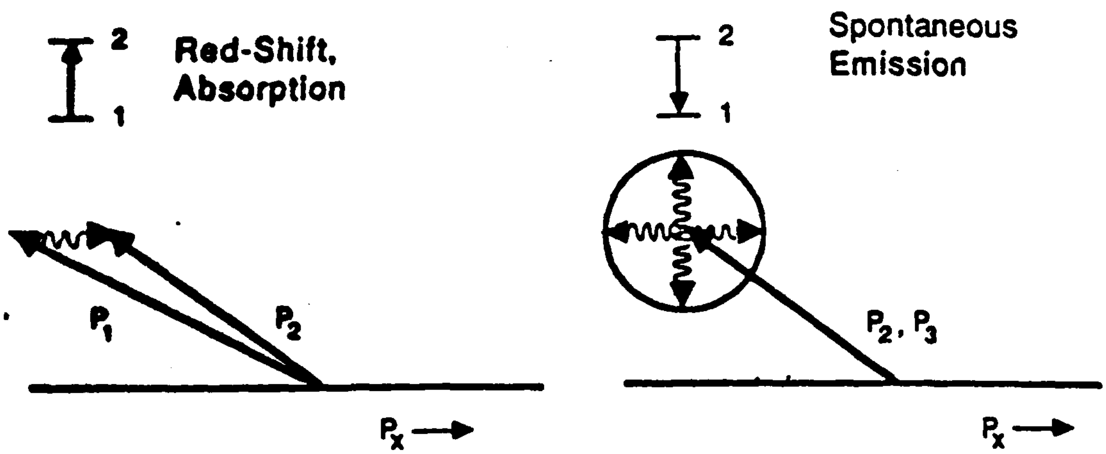
$\omega_0 =$ transition frequency
$\omega =$ laser frequency

detuning $\delta = \omega - \omega_0$

↑ Deepest potential at $\delta \doteq -\Gamma$
But severe heating of gas due to spont. emission

For Na Chu et al used $\delta \geq 10^3 \Gamma$ to minimize heating
but potential well - few mK





LASER SPONTANEOUS COOLING

Laser power is a major problem

For 1216 Å sources are pulsed, non-linear harmonic generators

Current sources $\sim 10^{10} \frac{\text{photons}}{\text{sec}}$ $\left(1 \text{ Watt} = 6 \times 10^{17} \frac{\text{photons}}{\text{sec}}\right)$

Very Large improvements possible

but still pulsed at ~ 30 hz

$t_{off} = 33$ msec

Trapped atoms rapidly expand during off time

trap dimensions ~ microns

$\bar{v}$ at 2.2 mk ~ 3 meters/sec

Off time expansion

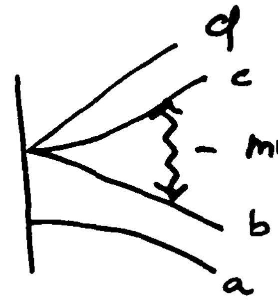
$\Delta x = \bar{v} \times t_{off} = 3 \text{ m/sec} \times 33 \text{ msec}$

$\approx 10 \cancel{0}$ cm !

New Trap: Microwave Trap

Agosta, Silvera, Verhaar + Stoof

Just like laser trapping, but no spontaneous emission



Dressed atoms: Diagonalize atomic states and radiation field (N-photons)

low field seeker

Dressed states

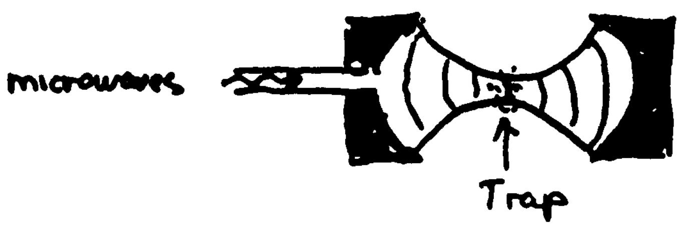
$$|1\rangle = \cos\theta\, |c, N-1\rangle + \sin\theta\, |b, N\rangle$$

$$|2\rangle = -\sin\theta\, |c, N-1\rangle + \cos\theta\, |b, N\rangle$$

high field seeker

State $|2\rangle$ seeks highest microwave field

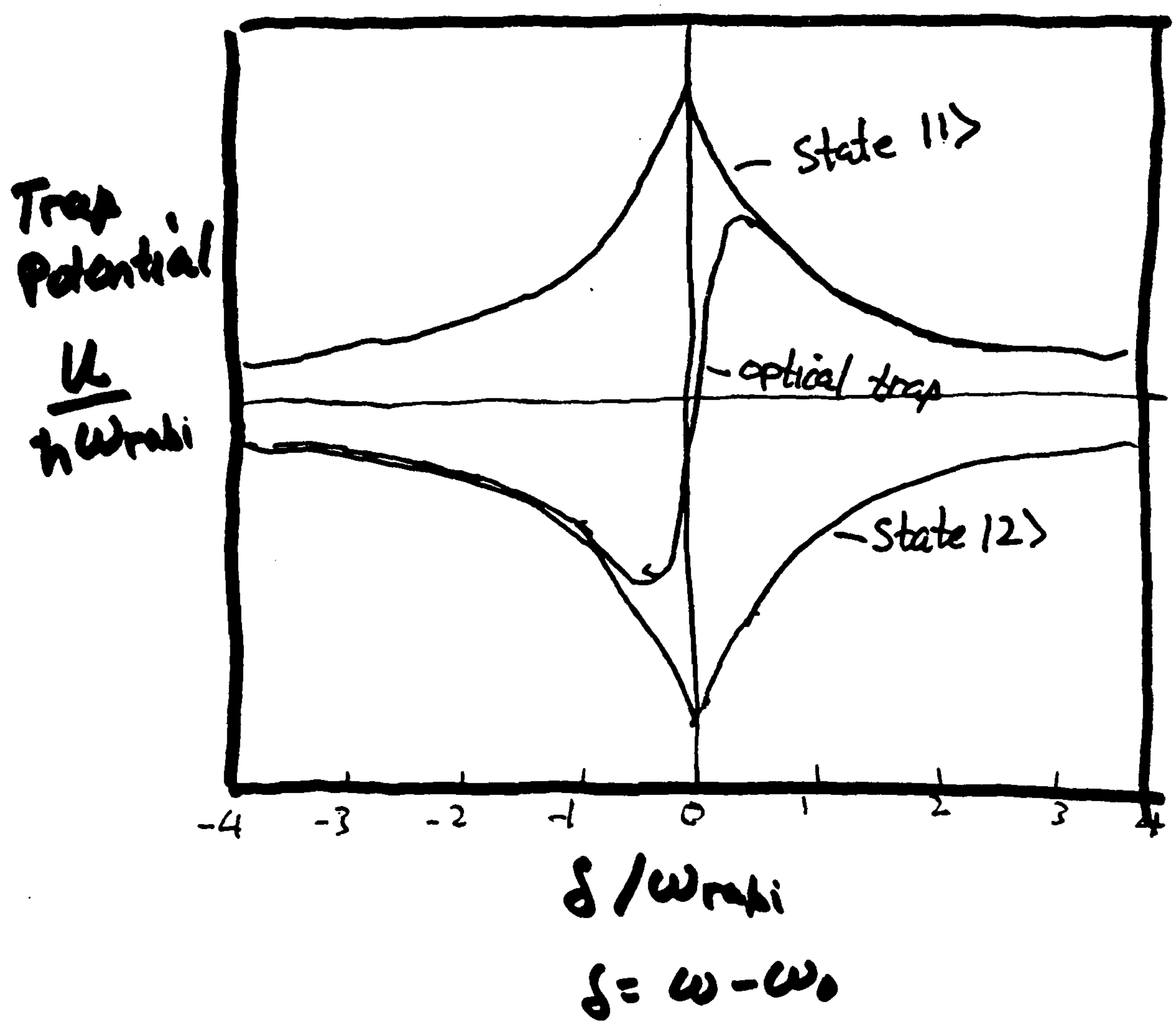
Confocal resonator cavity



$$U_{trap} = \frac{\hbar}{2}\,\omega_{rabi}$$

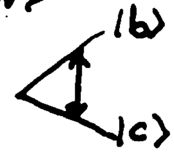
$$\omega_{rabi} \simeq \mu_{bc} B_{microwave}$$

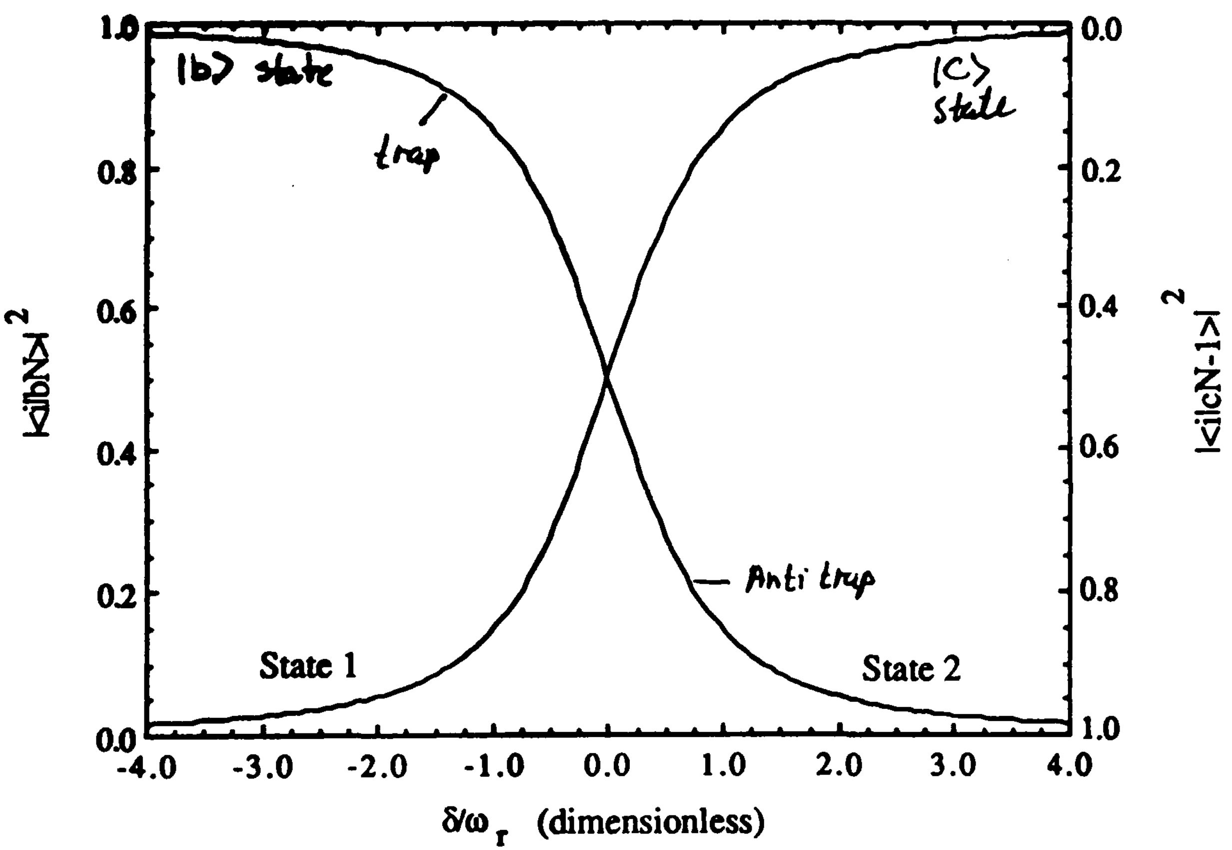
$$\therefore \quad U_{trap} = \frac{\hbar}{2}\mu_{bc} B_{microwave}$$



Trap potential
$\frac{U}{\hbar\omega_{rabi}}$
State $|1\rangle$
optical trap
State $|2\rangle$
-4
-3
-2
-1
0
1
2
3
4
δ/ω_{rabi}
$\delta = \omega - \omega_0$

$|1\rangle = \cos\theta\, |c, N-1\rangle + \sin\theta\, |b, N\rangle$
$|2\rangle = -\sin\theta\, |c, N-1\rangle + \cos\theta\, |b, N\rangle$





Plot of the admixture of $|c\rangle$ or $|b\rangle$ states into $|1\rangle$ or $|2\rangle$ states.

FIG. 1B

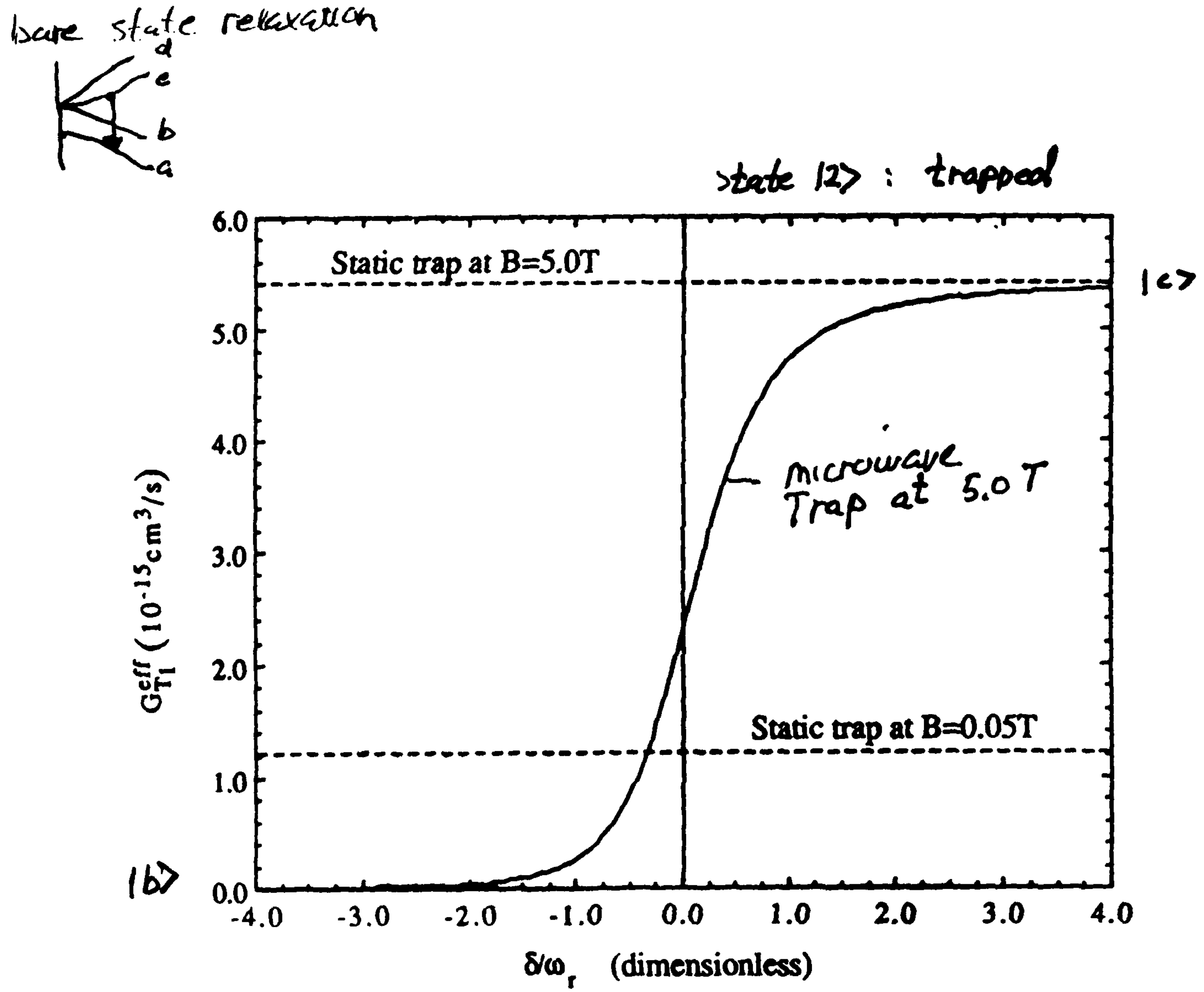

bare state relaxation
d
e
b
a
state |2> : trapped
Static trap at B=5.0T
|c>
microwave Trap at 5.0 T
Static trap at B=0.05T
|b>
G_{T1}^{eff} $(10^{-15} cm^3/s)$
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
4.0
δ/ω_r (dimensionless)

FIG. 2

Advantages of μ-wave trap

No spontaneous heating $\tau_{spont} \approx 10^7$ years

Microwave Technology well developed

Difficulties

- Require microwave fields of several hundred gauss at $\nu \sim 50$ Ghz.
- Has not yet been built (Article To appear PRL next week)

Loading - A long story for another ~~occasion~~ time

ANTIHYDROGEN PRODUCTION

ARTHUR RICH

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PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

Anti-Hydrogen: Formation and Applications

Presented by: Arthur Rich
Physics Dept.
University of Michigan

Anti-Hydrogen: Formation and Applications

I – Introduction

II – Methods of $\bar{H}$ Production

A – Overview

B – Specific Methods

i. $e^+ + \bar{p} \rightarrow \bar{H} + h\nu$ (~~1 pass and~~ recirculating e^+ beam)

ii. $e^+ + \bar{p} + nh\nu \rightarrow \bar{H} + (n+1)h\nu$ $(n = 0, 1, 2 \cdots)$

iii. $Ps + \bar{p} \rightarrow \bar{H} + e^-$

iv. $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$

III – $\bar{H}$ – Applications

IV – Conclusions

2.

COLLABORATORS

UNIVERSITY OF MICHIGAN - EXPERIMENTAL

RALPH CONTI - POSITRONIUM (Ps) 1^3S_1 DECAY RATE (λ_T) FINE STRUCTURE (n=2) TRANSITIONS AND CP TEST; ANTI-HYDROGEN ($\overline{H}$) FORMATION

WILLIAM FRIEZE - e^+ - Ps CONDENSED MATTER RESEARCH; e^+ IMAGING; $\overline{H}$

DAVID GIDLEY - λ_T (Gas and Vacuum); e^+ - Ps CONDENSED MATTER AND POLARIZED e^+ SURFACE MAGNETISM RESEARCH; e^+ IMAGING; $\overline{H}$

HENRY GRIFFIN (CHEMISTRY) - INTENSE e^+ SOURCE DEVELOPMENT ($\overline{H}$)

JEFFREY NICO - λ_T (Vacuum)

MARK SKALSEY - WEAK INTERACTION TESTS via PRECISION BETA DECAY POLARIZATION MEASUREMENT, INTENSE e^+ SOURCE DEVELOPMENT

TOM STEIGER - INTENSE e^+ SOURCE DEVELOPMENT ($\overline{H}$)

JAMES VAN HOUSE - SEARCH FOR e_- HELICITY IN OPTICALLY ACTIVE MOLECULES USING POLARIZED e^+ BEAMS; e^+ IMAGING; $\overline{H}$

PAUL ZITZEWITZ - λ_T (Vacuum); $\overline{H}$; OPTIMIZATION OF POLARIZED e^+ BEAMS

UNIVERSITY OF MICHIGAN - THEORETICAL

WILLIAM FORD	ROBERT LEWIS	YUKIO TOMOZAWA
GORDON KANE	LEONARD SANDER	EDWARD YAO

UNIV. OF TORONTO	PRINCETON UNIV.
DEREK PAUL	FRANK CALAPRICE

WEAK INTERACTIONS

CERN-HEIDELBERG-DARMSTADT	WAKE FOREST UNIV.	GM RESEARCH LAB
HELMUT POTH, et al.	ROGER HEGSTROM	WESTRUM CAPEHART
ANTI-HYDROGEN	ORIGIN OF BIOLOGICAL ACTIVITY	SURFACE MAGNETISM

3

$\overline{\mathrm{H}}$ APPLICATIONS

1. TCP Tests

   Hyperfine Structure

   Lamb Shift

   Fine Structure

   Electronic Structure ($\overline{\mathrm{Rydberg}}$) and $m_{\bar{p}}$ (inertial), $\mu_{\bar{p}}$

2. Production of Polarized $\bar{p}$

   i. Transfer of Polarization from an Initially Polarized e^+ Beam -

   $e^+(\uparrow) + \bar{p} \rightarrow \overline{\mathrm{H}}(\uparrow) \rightarrow e^+(\uparrow) + \bar{p}(\uparrow)$

   ii. Optical pumping, Resonant Ionization, Lamb Shift Spin Filter -

   $e^+ + \bar{p} \rightarrow \overline{\mathrm{H}};\quad \overline{\mathrm{H}} + nh\nu \rightarrow \overline{\mathrm{H}}(\uparrow) \rightarrow \bar{p}(\uparrow) + e^+(\uparrow)$

3. Astrophysics

   $\overline{\mathrm{H}} + \mathrm{H} \rightarrow [\bar{p}p + Ps;\quad \bar{p} + p + Ps;\quad \bar{p}p + e^+ + e^-;\quad \bar{p} + p + e^+ + e^-]$

   $\overline{\mathrm{H}} + \mathrm{H} \rightarrow \overline{\mathrm{H}} + \mathrm{H}$

4. $\overline{\mathrm{H}}$ - Gravity Interaction

   $m_{\bar{p}}$ *(inertial)*/m_p *(inertial)* - $[\omega(\overline{\mathrm{H}} - hfs)/\omega(\mathrm{H} - hfs)]$

   $m_{\bar{p}}$ gravitational -

5. Atomic Physics

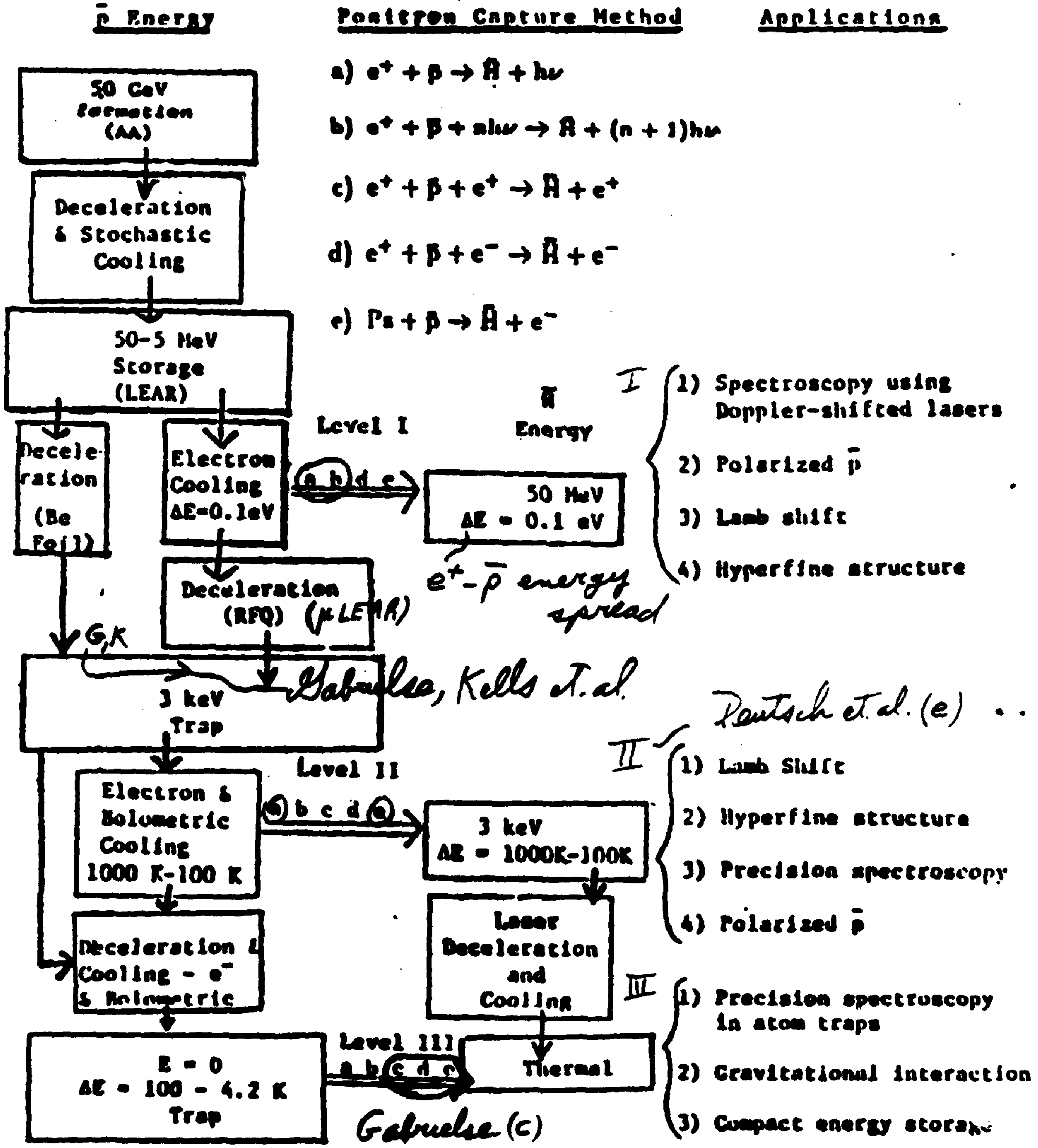
   $\overline{\mathrm{H}}$ + Matter $\longrightarrow$ $\bar{p} + e^+$ + Matter (stripping)

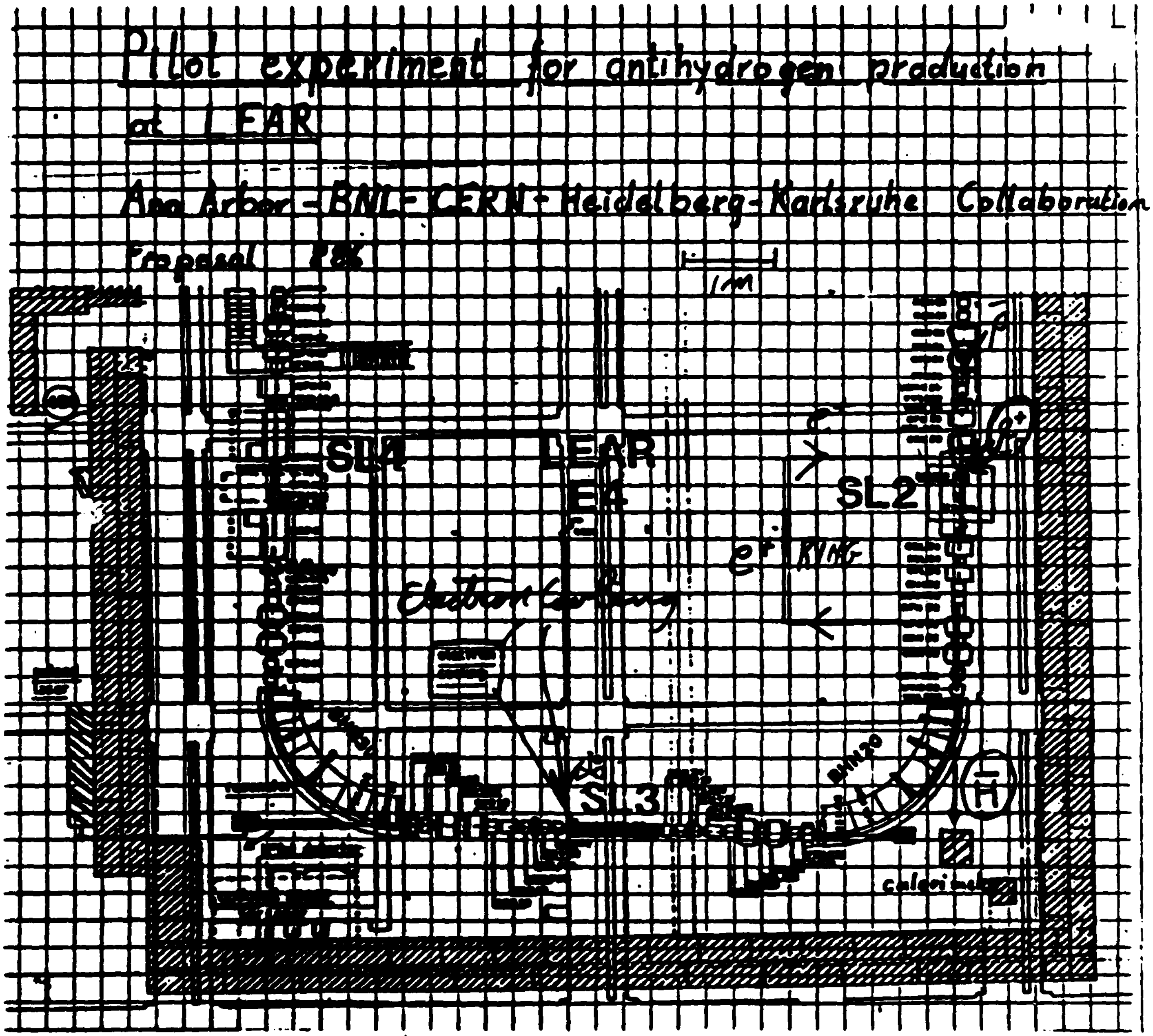
   $\overline{\mathrm{H}}$ + Matter $\longrightarrow$ $\overline{\mathrm{H}}$ + Matter (elastic and inelastic scattering)

6. $\overline{\mathrm{H}}$ - Energy storage

7.

$\bar{H}$ Production




Pilot experiment for antihydrogen production
at LEAR
Ann Arbor - BNL - CERN - Heidelberg - Karlsruhe Collaboration
Proposal
1 M
SL1
LEAR
E4
SL2
e⁺ RING
Electron Cooling
SL3
BHN20
calorimeter

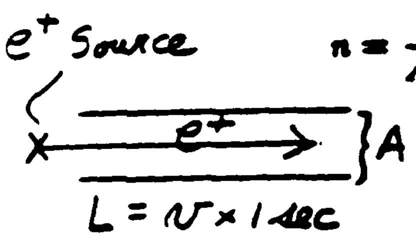
6.

$\bar{H}$ Production by Radiative Recombination – Projected Rates (1 pass)

Assume equal area, non-relativistic, $\bar{p}$ and e^+ beams. Then

$$R(e^+ + \bar{p} \to \bar{H} + h\nu) \approx n(e^+) \langle \sigma v_r(e^+ - \bar{p}) \rangle \, (N(\bar{p})\eta)$$

where: $n(e^+) = e^+/\mathrm{cm}^3$ in $(e^+, \bar{p})$ overlap region



$$n = \frac{R(e^+/s)}{A(L = v \times 1\ \mathrm{sec})} \sim \frac{\overbrace{(4 \times 10^{11})}^{10\ \mathrm{Ci}\ -\ {}^{22}\mathrm{Na}} \times \overbrace{(10^{-4})}^{1\ \mathrm{Remoderation}}}{\underbrace{10^{-2}\ \mathrm{cm}^2}_{A} \times \underbrace{10^{10}\ \mathrm{cm}}_{L}} \sim 1\ \mathrm{cm}^{-3}$$

$$\frac{\alpha}{c^2}\omega^3 a_0^2 = \frac{\alpha}{c^2}\left(\frac{\alpha c}{a_0}\right)^3 a_0^2 = \alpha^4 c/a_0$$

γ $\quad \Delta T \longrightarrow a_0/v_r$

$$\sigma_1(\infty \to 1) = 2\pi\left[(\pi a_0^2)\overbrace{\left(\frac{\alpha^4}{\beta_r}\right)}\left(\frac{\alpha}{\beta_r}\right)\right] = \frac{2\pi^2 \alpha r_e^2}{\beta_r^2}\ \mathrm{cm}^2$$

$$\sigma = \sum \sigma_i \sim 3\sigma_1 \sim 0.5 r_e^2/\beta_r^2$$

$$\underbrace{\langle \sigma v_r \rangle}_{\alpha_r} \sim \frac{0.5 r_e^2 c}{\langle \beta_r \rangle} \sim \frac{(4 \times 10^{-26}) \times (3 \times 10^{10})}{6 \times 10^{-4}} \sim 2 \times 10^{-12}\ \mathrm{cm}^3/\mathrm{s}$$

$T_r \sim 0.1\,\mathrm{eV}$

$N(\bar{p})$ = **number of $\bar{p}$ stored in LEAR $\approx 10^{11}$** (Cooled - 10^{10})

η = **fraction of $\bar{p}$ ring overlapped by e^+ beam $\approx$ 4m/80m $\simeq$ 0.05**

$$R \sim 1 \times (3 \times 10^{-12}) \times (5 \times 10^{9}) \sim 10^{-2}/\mathrm{s} \sim 30\mathrm{hr}^{-1}\ (3\,h^{-1})$$

7.

$\bar{H}$ Production by Radiative Recombination Using Recirculating e^+

$$R_S(e^+ + \bar{p} \rightarrow \bar{H}) \approx \underbrace{n_S(e^+)}\ \overset{3\times10^{-12}}{\alpha_r}\ (\overset{10^{11}}{N(\bar{p})}\ \overset{0.05}{\eta})$$

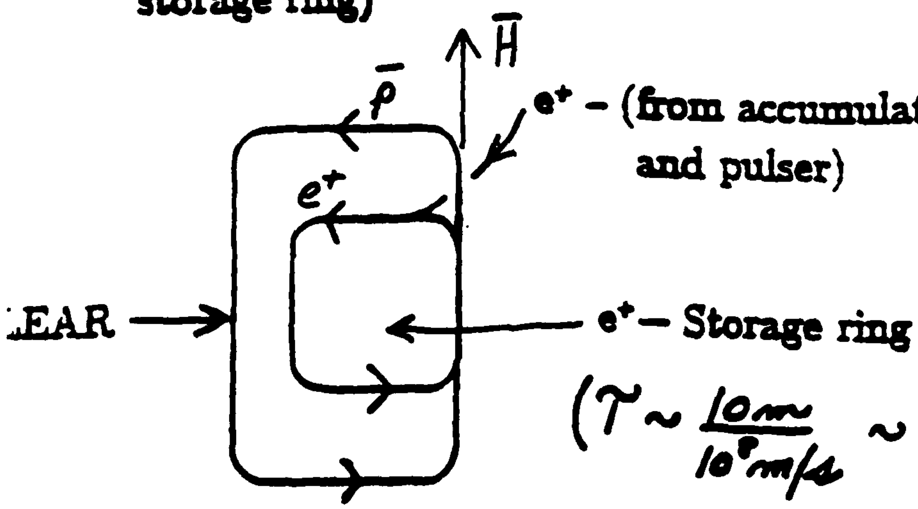
(fraction of $\bar{p}$ ring occup. by e^+)

$$\alpha_r \equiv \langle \sigma v_r \rangle \simeq \frac{r_e^2}{\beta_r^2}\, v_r \sim 10^{-19} \times 10^{7}$$

10 Ci Remoderate and store-1s

$$0.1\,eV \qquad n_S \equiv \frac{R(e^+/s)}{A(L = 10^3\,\mathrm{cm})} = \frac{(4\times10^{11})\times 10^{-5}}{10^{-2}\times 10^{3}} \sim 4\times10^{6}\ cm^{-3}$$

e^+ - accumulated, cooled, pulsed and recirculated (10 m e^+ storage ring)



$$\left(\tau \sim \frac{10\,m}{10^{8}\,m/s} \sim 100\,ns\right)$$

$$R_S(e^+ + \bar{p} \rightarrow \bar{H}) = \overbrace{(4\times10^{6})}^{n_S} \times \overbrace{(3\times10^{-12})}^{\alpha_r} \times \underbrace{(5\times10^{9})}_{N(\bar{p})\eta} \sim 6000\ /s$$

$\bar{H}$ Production by Radiative Recombination : Recirculating e⁺ and Stimulated Recombination

$$R_S(e^+ + \bar{p} \rightarrow \bar{H}) \approx \underbrace{n_S(e^+)}_{}\overbrace{\alpha_R}^{3\times10^{-12}}\overbrace{(N(\bar{p})\eta)}^{5\times10^{7}}G$$

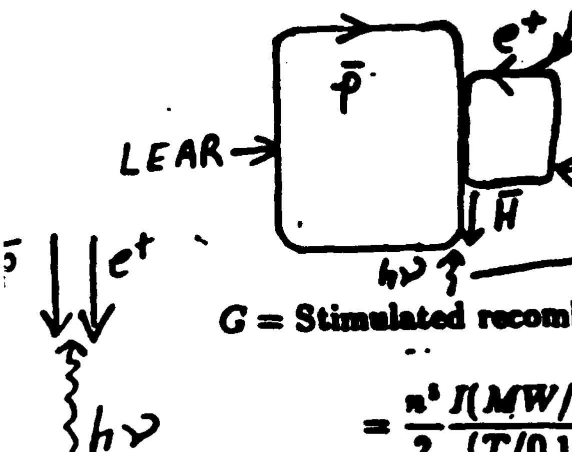
Laser recomb. gain factor

Recomb. and storage per 1 sec

e⁺ storage

$$n_S \equiv \frac{R(e^+/s)}{A(L = 10^3\text{cm})} = \frac{(4\times10^{11})\times10^{-5}}{10^{-2}\times10^{3}} \sim 4\times10^{5}\ \text{cm}^{-3}$$

e⁺ - accumulated, cooled, pulsed and recirculated (10 m e⁺ storage ring)



e⁺ e⁺ (from accumulator and pulser)

e⁺ Storage ring ($\tau \sim \frac{10\text{ m}}{10^8\text{ m/s}} \sim 100$ ns)

Laser radiation (Pulsed or CW)

G = Stimulated recombination gain factor $(e^+ + \bar{p} + h\nu \rightarrow \bar{H} + 2h\nu)$ =

$$= \frac{n^3}{2}\frac{I(MW/\text{cm}^2)}{(T_r/0.1\text{eV})}$$

If $\lambda_{Lab} = 521$ nm$(\lambda_{CM} = \lambda_L(1-\beta)\gamma = 364$ nm for $\infty \rightarrow 2)$

n = 2

n = 1

then $G \sim 16\ I$ for $T_r \sim 0.1$ eV

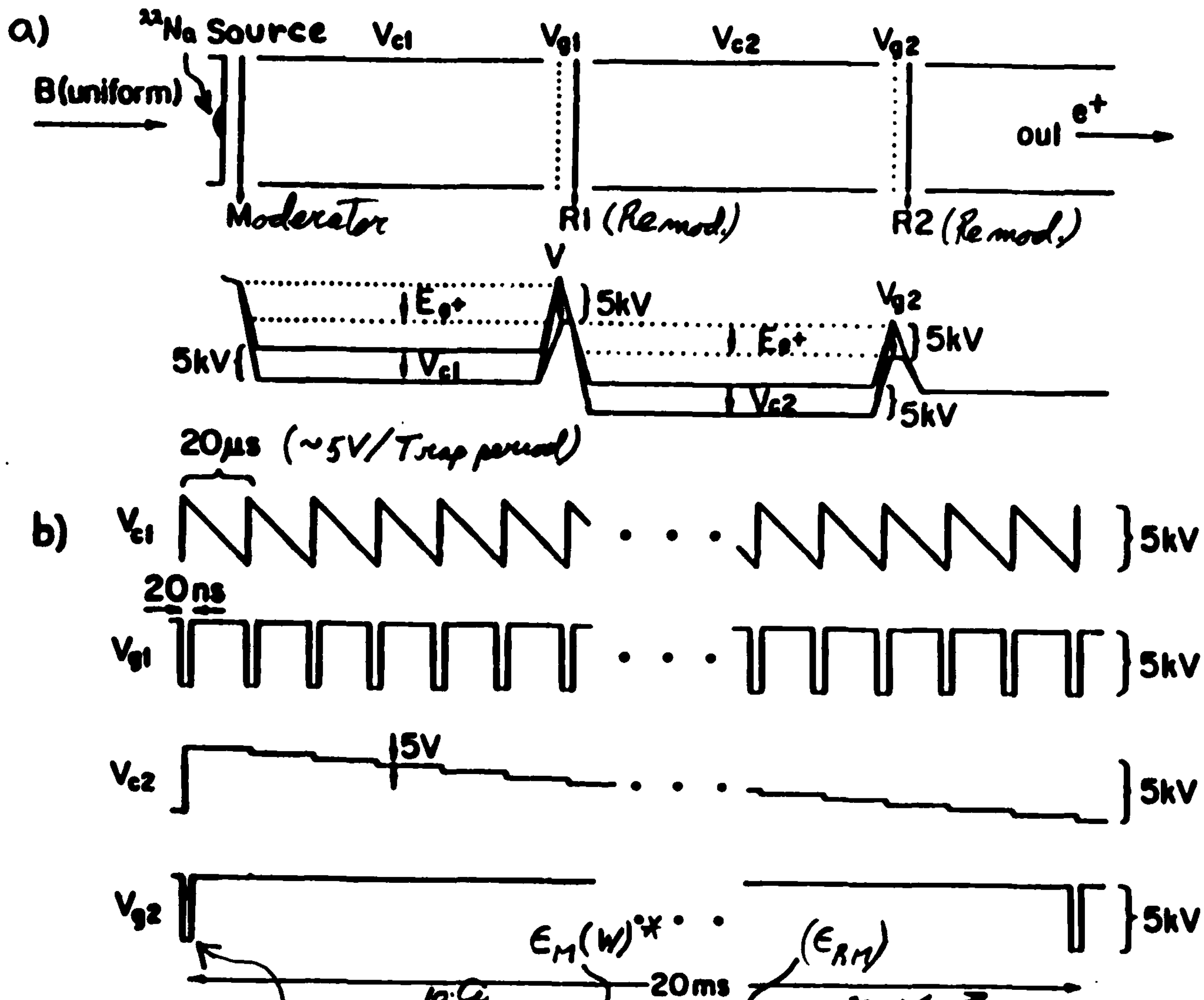
Commercial 20 MW/cm² excimer laser (250 Hz, 20 ns pulse) $G \sim 10^2$

Finally - If pulsed e⁺ matches laser (stored pulse)

$$R_S(e^+ + \bar{p} \rightarrow \bar{H}) = \overbrace{(4\times10^{5})}^{n_S}\times\overbrace{(3\times10^{-12})}^{\alpha}\times\overbrace{(5\times10^{9})}^{N_{\bar{p}}\eta}(G) \sim 6000\ G/s$$

<u>CW</u> - (CO/CO₂ ~ 20 W), n > 10, G ~ 10³ <u>but</u> re-ionization and field ionization problems

Positron Accumulator and Pulser



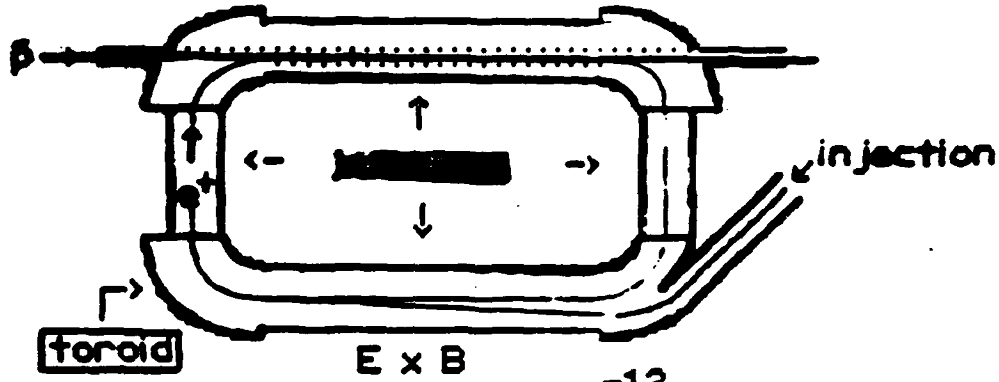
$$\#\text{ of } e^+/\text{pulse} \sim \overbrace{4\times10^{11}}^{10\cdot Ci} \times \underbrace{(3\times10^{-4})}_{} \left(\tfrac{1}{3}\right)^2 \times \overbrace{20\times10^{-3}}^{20\,ms} \sim 2\times10^5/\text{pulse}$$

$$\text{〃} \;/\text{sec} \sim 2\times10^5\times50 \sim 10^7/s$$

$\boxed{{}^*\epsilon_M(Ne) \sim 10^2\,\epsilon_M(W)}$

Positron recirculator

a) circular device

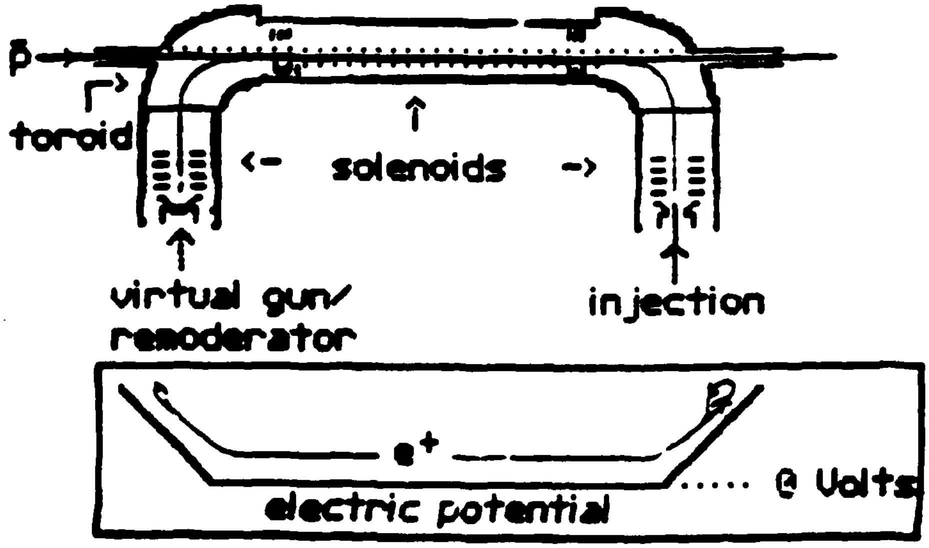


circumference: 15 m, vacuum: 10^{-12} Torr

magnetic field 200–600 G, e^+ energy: 20–100 keV

---

b) linear device



$\overline{\mathrm{H}}$ APPLICATIONS

1. TCP Tests

   Hyperfine Structure
   Lamb Shift
   Fine Structure

   $\left.\begin{array}{l}\text{Hyperfine Structure}\\ \text{Lamb Shift}\\ \text{Fine Structure}\end{array}\right\}$ $N \sim 10$ cycles/m at $\beta \sim 0.3$

   Electronic Structure ($\overline{\text{Rydberg}}$) and $m_{\bar{p}}$ (inertial), $\mu_{\bar{p}}$

2. Production of Polarized $\bar{p}$

   i. Transfer of Polarization from an Initially Polarized e^+ Beam -

   $e^+(\uparrow) + \bar{p} \rightarrow \overline{H}(\uparrow) \rightarrow e^+(\uparrow) + \bar{p}(\uparrow)$

   $P_i(e^+)$ $\quad P_f(e^+) \sim \frac{1}{2} P_i(e^+)$; $P(\bar{p}) \sim \frac{1}{2} P_i(e^+)$

   ii. Optical pumping, Resonant Ionization, Lamb Shift Spin Filter -

   $e^+ + \bar{p} \rightarrow \overline{H}$; $\quad \overline{H} + nh\nu \rightarrow \overline{H}(\uparrow) \rightarrow \bar{p}(\uparrow) + e^+(\uparrow)$

3. Astrophysics

   $\overline{H} + H \rightarrow [\bar{p}p + Ps; \quad \bar{p} + p + Ps; \quad \bar{p}p + e^+ + e^-; \quad \bar{p} + p + e^+ + e^-]$

   $\overline{H} + H \rightarrow \overline{H} + H$

4. $\overline{H}$ - Gravity Interaction

   $m_{\bar{p}}$ *(inertial)*$/m_p$ *(inertial)* - $[\omega(\overline{H} - hfs)/\omega(H - hfs)]$

   $m_{\bar{p}}$ gravitational -

5. Atomic Physics

   $\overline{H}$ + Matter $\longrightarrow$ $\bar{p} + e^+$ + Matter (stripping)

   $\overline{H}$ + Matter $\longrightarrow$ $\overline{H}$ + Matter (elastic and inelastic scattering)

6. $\overline{H}$ - Energy storage

Anti-Proton Polarization via $\bar{H}$ Formation with Polarized Positrons

1. $\bar{H}$ hfs $(n=1)$

$$\begin{array}{lll}
\text{Triplet} & \longrightarrow & \overbrace{\Downarrow\downarrow}^{e^+\ \bar{p}},\ \Uparrow\uparrow,\ \overbrace{\tfrac{1}{\sqrt{2}}(\Uparrow\downarrow+\Downarrow\uparrow)}^{\psi_T(m=0)} \\
\downarrow & \leftarrow \omega & [1.5\,\mathrm{GHz},\ \tau\simeq 10^{-9}\,\mathrm{s},\ N\simeq 10\,L(m)] \\
\text{Singlet} & & \underbrace{\tfrac{1}{\sqrt{2}}(\Uparrow\downarrow-\Downarrow\uparrow)}_{\psi_S}
\end{array}$$

# of hfs cycles for $\beta=0.3$
$(L(\mathrm{hfs})\sim 10\,\mathrm{cm})$

2. $\bar{H}$ Formation from Polarized e^+ - Unpol. $\bar{p}$

$$(1/2)\quad \underset{e^+}{\Uparrow}+\underset{\bar{p}}{\uparrow}\longrightarrow\underset{\bar{H}}{\Uparrow\uparrow}\longrightarrow\Uparrow\underset{1/2}{+}\uparrow$$

$$(1/2)\quad \Uparrow+\downarrow\longrightarrow\Uparrow\downarrow\xrightarrow[t>\tau]{}\underbrace{\Uparrow+\downarrow}_{1/4}\ \text{or}\ \underbrace{\Downarrow+\uparrow}_{1/4}$$

$$\psi(\Uparrow\downarrow)=\frac{1}{\sqrt{2}}\left[\psi_T(m=0)\,e^{i\omega\tau}+\psi_S\right]=\begin{cases}\Uparrow\downarrow & \omega\tau=0\\ \Downarrow\uparrow & \omega\tau=\pi\end{cases}$$

3. $\bar{p}$ Polarization

$$P(\bar{p})=\frac{N(\uparrow)-N(\downarrow)}{N(\uparrow)+N(\downarrow)}=\frac{\left(\frac{1}{2}+\frac{1}{4}\right)-\frac{1}{4}}{1}=\frac{1}{2}\overbrace{P(e^+)}^{0.4}$$

Polarized $\bar{p}$ – Projected Rates

Rate

$$R_S(e^+ + \bar{p} \longrightarrow \bar{H}) = \overbrace{(4 \times 10^5)}^{n_S} \times \overbrace{(3 \times 10^{-12})}^{\alpha_r} \times \overbrace{(5 \times 10^8)}^{\text{Current } N(\bar{p})\eta} \overset{\text{Laser gain } (G \sim 10^2 - 10^3)}{G} \sim 600 \text{ G/s}$$

$$\xrightarrow{\text{Future (?)}} (5 \times 10^9) \quad \sim 6000 \text{ G/s}$$

Polarization

1) If no attempt is made to maximize $P(e^+)$, $P(e^+) \sim 0.15$

2) To increase $P(e^+)$ use Be absorber to reduce low energy e^+ from beta spectrum (recall $P_{Long} = \langle v \rangle / c$)

3) Maximize $P^2 I \Rightarrow P(e^+) = 0.5$ but $n_S = 1.5 \times 10^5$ (200 G/s)
(2000 G/s)

Result

$$R_S(\bar{H}) \sim R_S(\bar{p}) \sim (2 \times 10^7 - 2 \times 10^8) \text{ G/day at } P(\bar{p}) \simeq \tfrac{1}{2} P(e^+) \simeq 0.25$$

Polarized $\bar{p}$ – Projected Rates and Uses

$$\bar{p} + p \longrightarrow \begin{cases} \bar{p} + p \\ \pi^+ + \pi^- \\ K^+ + K^- \\ \bar{n} + n \end{cases}$$

$$A_{\parallel} = \frac{1}{P_{\bar{p}}P_p}\left[\frac{\sigma_T(\uparrow_{\bar{p}}\uparrow_p) - \sigma_T(\downarrow_{\bar{p}}\uparrow_p) - \sigma_T(\uparrow_{\bar{p}}\downarrow_p) + \sigma_T(\downarrow_{\bar{p}}\downarrow_p)}{\sigma_T(\uparrow_{\bar{p}}\uparrow_p) + \sigma_T(\downarrow_{\bar{p}}\uparrow_p) + \sigma_T(\uparrow_{\bar{p}}\downarrow_p) + \sigma_T(\downarrow_{\bar{p}}\downarrow_p)}\right]$$

where $P_{\bar{p}}$ and P_p are the longitudinal polarizations of the antiproton beam and proton target, respectively, and the σ_T are the measured total cross sections with the sense of polarizations indicated by the arrows. A similar asymmetry $A_{\perp}$ could be measured for the p and $\bar{p}$ polarized transversely to the incident $\bar{p}$ direction. Each asymmetry could be measured to a precision

$$\delta(A) = \frac{1}{\sqrt{N_{event}}\,P_{\bar{p}}P_p}$$

where N_{event} is the total number of $\bar{p}$ interacting in the target. If the target thickness is chosen so that 20% of the incident $\bar{p}$ interact in the target (a sufficiently small fraction to avoid degradation of the asymmetry by multiple scattering events) and given $P_{\bar{p}} = 0.25$ and $P_p \sim 0.12$, (P_p is a typical value for the effective proton polarization in a hydrocarbon target with 70% hydrogen proton polarization) then in one day of running one can attain

$$\delta(A) = \pm\frac{1}{\sqrt{0.2 \times 3 \times 10^7}\;0.25 \times 0.12} = \pm 0.01^{*}\ .$$

* $A_{\parallel}(pp) = 0.15$ ($p_{Lab} = 1.6$ GeV/c)

15.

CONCLUSIONS

I - HISTORY (e^+)

1932 - 72 HEROIC PERIOD

1972 - 85 R(slow e^+) $\sim (10^4 - 10^6)$/sec

$n(e^+/cm^3) \sim 1$

1985 → $R \sim 10^8/s$

$n \sim 10^6/cm^3$

II - FUTURE

INCREASE IN R, n ➡

1) IMPROVED QUANTUM ELECTRODYNAMICS AND SYMMETRY TESTS.

2) e^+ PLASMA.

3) e^+ IMAGING.

4) ANTI-HYDROGEN.

5) "BOSE-EINSTEIN" CONDENSATION OF POSITRONIUM.

$(\lambda_{deB} \sim n^{-1/3})$

HEADQUARTERS DOE ANTIPROTON ACTIVITIES

DAVE GOODWIN

OFFICE OF HIGH ENERGY AND NUCLEAR PHYSICS
U.S. DOE ER-20.1/GTN
WASHINGTON, DC 20545

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

WORKSHOP ON ANTIPROTON TECHNOLOGY

BROOKHAVEN, MAY 10, 1989

"HEADQUARTERS DOE ANTIPROTON ACTIVITIES"

DAVE GOODWIN

SPECIAL ASST. TO THE ASSOCIATE DIRECTOR OF THE
OFFICE OF HIGH ENERGY AND NUCLEAR PHYSICS (OHENP)

U.S. DOE, ER-20.1/GTN, WASH., D.C. 20545
(301) 353-4037 (FAX 5079), FTS 233-4037 (FAX 5079)

EFFORTS TO OBTAIN RESOURCES FROM PROGRAM OFFICES

AVERAGE SINCE 10/87 WORKSHOP:

- o ONE DOCUMENT PER WEEK
- o DISCUSS WITH 2 PEOPLE PER DAY

SUPERCONDUCTING SUPER COLLIDER (SSC) STUDY

MARCH 16, 1989 LETTER FROM DIEBOLD TO SCHWITTERS:
1995 PHYSICS FROM MEDIUM ENERGY BOOSTER (100 TO 200 GeV)
10/2-4/89 OPEN HOUSE IN TEXAS

JIM BENSINGER (BRANDEIS), ROOM 2089C, SSC/URA, c/o LBL, 90/4040, BERKELEY, CA 94720, (415) 486-4772 EXT. 6083, FTS 451-4772 EXT. 6083, FAX (415) 486-6796

PROVIDED: U. OF MICH. LETTER, 10/88 AND 2/89 RAND REPORTS AND 14 REPLIES TO SURVEY LETTER

DOCUMENTS: 5 (INCL. FY91 FUNDING ISSUE FOR SSC/BROOKHAVEN)

STATUS: OPEN

<u>SUPERCOMPUTERS</u>

FY88: WORKSHOP ANNOUNCEMENT, NO PROPOSALS

FY89: RFTPs TO 54 WORKSHOP ATTENDEES
ONE PROPOSAL: TAKAHASHI (280 "HOURS"; \$100+K)
UP TO 60+HOURS/MONTH AVAILABLE

FY90: 5/15/89 SUPERCOMPUTER ALLOCATIONS COMMITTEE MEETING:
90,000 HOURS FOR HIGH ENERGY PHYSICS (HEP)/SSC, NUCLEAR PHYSICS (NP), BASIC ENERGY SCIENCES (BES) & HEALTH ENVIRONMENTAL RESEARCH (HER); EXCL. 27,000 HOURS FOR FUSION
RFTPs TO MOST ATTENDEES OF BOTH WORKSHOPS AND MIRROR MATTER NOTICE
TAKAHASHI: 380 HOURS (< \$150K)

DOCUMENTS: 2

STATUS: OPEN

10/11/88 SURVEY LETTER

319	HEP/SSC
210	NP
271	DOD
54	WORKSHOP ATTENDEES
1	U. OF N.C.
387	MIRROR MATTER
1,242	

14 REPLIES (MIRROR MATTER SUMMARIZES): NONE NEGATIVE

BES & HER: 14 REPLIES, 10/88 RAND REPORT & 5/89 WORKSHOP NOTICE WITH 2/89 RAND REPORT

15TH REPLY: LIPTHANE

DOCUMENTS: 9 STATUS: "CLOSED"

TECHNOLOGY TRANSFER

3/28-29/89: DOE TECHNOLOGY TRANSFER WORKING GROUP:

- LOS ALAMOS, BERKELEY, OAK RIDGE, PACIFIC NORTHWEST, DEFENSE PROGRAMS (DP) AND FUSION

5/9/89: ER TECHNOLOGY TRANSFER STEERING GROUP

- BROOKHAVEN, BERKELEY, OAK RIDGE, ARGONNE, PACIFIC NORTHWEST, BES, HER AND FUSION

4/4/89: $5 MIL./YR. FOR "SMALL SCIENCE" IMAGING/ANALYSIS AND ENERGY DEPOSITION WITH BES, HER, DP, NIH AND MINORITY EDUCATION ($20 MIL./YR.)

FY90 REQUEST FOR SMALL SCIENCE & SUGGESTION FOR MINORITY EDUCATION

DOCUMENTS: 3 STATUS: OPEN

SMALL BUSINESS INNOVATION RESEARCH (SBIR)

RECALL MIRROR MATTER: \$50K, \$500K

FY88: ELECTRON COOLING (D. LARSON)
2 TRANSPORTERS (W. WING)
LASER COOLING (" ")
RELATIVISTIC SELF-COLLIDER: RESCOL (B. MAGLICH)

FY89: ANTIPROTON TOPIC (OHENP SIGN): "PREMATURE"
ELECTRON COOLING (D. LARSON)

FY90 SBIR

HEP/SSC/NP MAY REDUCE FROM 6 TOPICS TO 3 - 5

5/4/89: ANTIPROTON TOPIC

PROVIDED: 15 SURVEY REPLIES, 10/88 & 2/89 RAND REPORTS,
SSC STUDY, SUMMARY FOR HUNTER & BROOKHAVEN PAPER

WILL NEED REVIEWERS

DOCUMENTS: 2

STATUS: OPEN

WEEKLY/BIWEEKLY REPORTS

WEEKLY: FROM OHENP THRU OFFICE OF ENERGY RESEARCH (OER) TO SECRETARY & ALL DOE PROGRAM & OPERATIONS OFFICES

BIWEEKLY: FROM OHENP TO ALL ER OFFICES (INCL. HEP, SSC, NP, BES, HER AND FUSION)

MONTHLY: TO ALL DOE OPS OFFICES AND ER OFFICES

10/87 WORKSHOP: WEEKLY, BIWEEKLY AND MONTHLY

12/1/87 AFAL BRIEFING (OHENP, HEP, BES & HER ATTEND):
2 WEEKLY, BIWEEKLY, MONTHLY, NOTICES AND MINUTES (TO OER, ALL HEP/SSC & NP STAFF & BES, HER, FUSION & DP)

WEEKLY/BIWEEKLY REPORTS

7/26/88 AFAL/AFOSR MEETING: WEEKLY AND BIWEEKLY

3/24/89 SDIO & 3/27/89 NASA MEETINGS: WEEKLY & BIWEEKLY

5/89 WORKSHOP: 1ST OF 2 WEEKLY, 1ST OF 2 BIWEEKLY & NOTICE TO OHENP, ALL HEP/SSC & NP STAFF & BES, HER FUSION & DP, WITH 2/89 RAND REPORT

RAND ASSOCIATED PRESS ITEM: WEEKLY AND BIWEEKLY

G-2: WEEKLY, BIWEEKLY, MONTHLY & MEMOS (INCL. 14 SURVEY REPLIES)

LEAR: WEEKLY & BIWEEKLY (4/17/89 LETTER FROM 3RD VERY RELIABLE SOURCE): STATUS OF LEAR AFTER 1992 ?

ANNUAL REPORT TO CONGRESS

DOCUMENTS: 28 STATUS: CONTINUING ACTION

<u>FY88</u> <u>JASON</u> <u>STUDY</u>

OER MEETING WITH JASON

DOCUMENTS: 3 STATUS: CLOSED

<u>KAON</u>

(<u>K</u>AONS, <u>A</u>NTIPROTONS, <u>O</u>THERS STRONGLY INTERACTING PARTICLES & <u>N</u>EUTRINOS)

NUCLEAR SCIENCE ADVISORY COMMITTEE (NSAC) REPORT

PROVIDED NP WITH 14 SURVEY REPLIES

AFTER CEBAF & RHIC

DOCUMENTS: 2 STATUS: "OPEN"

PROPOSED USAF/HUNTER MEETING

SUMMARY TO HUNTER (SIGNED BY NP) PROVIDED TO OHENP, ALL HEP/SSC & NP STAFF & BES, HER, FUSION & DP

DOE POINT-OF-CONTACT

DOCUMENTS: 2 STATUS: "CLOSED"

TEXAS ACCELERATOR CENTER (TAC)

$3 MIL. FROM CONGRESS

TAC PARTICIPATION SUGGESTED IN TRIP REPORT ON 10/87 WORKSHOP (PROVIDED TO OER, OHENP, ALL HEP/SSC & NP STAFF & BES, HER, FUSION & DP)

AS OF 8/1/89: NO FURTHER HEP/SSC FUNDING

DOCUMENTS: 1 STATUS: "OPEN"

ACCELERATOR PRODUCED TRITIUM (APT)

PROPOSED ANSWER TO SENATE QUESTION INCLUDED ANTIPROTONS

JASON & 2/89 RAND REPORTS TO DP (INCL. CONGRESSIONAL LIASON)

ENERGY RESEARCH ADVISORY BOARD (ERAB) SUBPANEL & GAO

EXYDER (XY SELF-COLLIDER):

- O $17.628 MIL. FOR 2 1/2 YR., 10 KG/YR. OF ANTIPROTONS
  INFO. TO DP INCL. ANTIPROTONS
- o 2/4/88 MIGMA MEETING WITH HEP, BES & FUSION (1 G/YR)

DOCUMENTS: 9 STATUS: "CLOSED"

SMALL/DISADVANTAGED BUSINESS (8A)

UP TO $170K/YR.

DOCUMENTS: 7 (IN 1 OF 5 STATUS REPORTS TO AFAL/ANTI-M)

STATUS: "OPEN" (NEED PROPOSAL)

RAND REPORT ON REMOTE POWER

WITH 2/89 RAND REPORT TO: DP, NUCLEAR MATERIALS PRODUCTION & SP-100

DOCUMENTS: 3 STATUS: "OPEN"

ANNUAL MEETING OF NUCLEAR PHYSICS LAB DIRECTORS

RECOMMENDED AGENDA ITEM ON ANTIPROTONS

DOCUMENTS: 1 STATUS: OPEN

INSTITUTIONAL PLANNING REVIEWS

RECOMMENDED AGENDA ITEM ON ANTIPROTONS FOR FY88 BROOKHAVEN REVIEW

FY89: 9/13/89 FERMILAB & 7/17-18/89 BROOKHAVEN REVIEWS

ALSO: 8/15-24/89 "PHYSICS AT FERMILAB IN THE 1990S"

DOCUMENTS: 6 STATUS: OPEN

THE PLANETARY SOCIETY

PROVIDE REFS FOR 9/85 AFAL REPORT & WORKSHOP PROCEDINGS

DOCUMENTS: 1 STATUS: OPEN

OER & OHENP INFORMED

OER: 8 WEEKLY, 7 BIWEEKLY, 3 MONTHLY, JASON MEETING, SUMMARY FOR HUNTER, WORKSHOP: RAND & TRIP REPORTS, AFAL BRIEFING MINUTES AND 7 INFORMAL DISCUSSIONS

OHENP: SIGN 8 WEEKLY, 7 BIWEEKLY, SBIR & AFAL BRIEFING (ATTEND); SUMMARY FOR HUNTER, 3 MONTHLY, WORKSHOP: RAND & TRIP REPORTS, AFAL BRIEFING MINUTES, 5/89 WORKSHOP NOTICE WITH 2/89 RAND REPORT, FY90 FUNDS, SSC, BROOKHAVEN, 14 SURVEY REPLIES, 7 PAPERS/ETC. & 22 INFORMAL DISCUSSIONS

<u>HEP/SSC</u> <u>&</u> <u>NP</u> <u>INFORMED</u>

<u>HEP/SSC:</u> 7 BIWEEKLY, 3 MONTHLY; <u>ALL</u> <u>STAFF:</u> SUMMARY FOR HUNTER, WORKSHOP TRIP REPORT, AFAL BRIEFING MINUTES ("ATTEND") & 5/89 WORKSHOP NOTICE WITH 2/89 RAND REPORT; WORKSHOP RAND REPORT, FERMILAB, BROOKHAVEN, SSC, 14 SURVEY REPLIES, <u>40</u> PAPERS/ETC., WEEKLY STAFF MEETINGS & INFORMAL DISCUSSION WITH 1 PERSON EVERY OTHER DAY

<u>NP:</u> 7 BIWEEKLY, 3 MONTHLY; <u>ALL</u> <u>STAFF:</u> SUMMARY FOR HUNTER <u>(SIGN)</u>, WORKSHOP TRIP REPORT, AFAL BRIEFING MINUTES & 5/89 WORKSHOP NOTICE WITH 2/89 RAND REPORT; <u>KAON</u>/SSC, ANNUAL MEETING, WORKSHOP: RAND REPORT, 14 REPLIES, 1 PAPER, WEEKLY STAFF MEETINGS & INFORMAL DISCUSSION WITH 1 PERSON EVERY OTHER DAY

DP & FUSION INFORMED

DP: TECHNOLOGY TRANSFER, CLASSIFIED RAND REPORT, REMOTE POWER, APT/EXYDER, SUMMARY FOR HUNTER, AFAL BRIEFING, WORKSHOP: RAND & TRIP REPORTS, 4 PAPERS/ETC. (INCL. SDIO MEETING WEEKLY) AND 10 INFORMAL DISCUSSIONS

FUSION: 7 BIWEEKLY, 3 MONTHLY, SUMMARY FOR HUNTER, WORKSHOP TRIP REPORT, AFAL BRIEFING MINUTES, 5/89 WORKSHOP WITH 2/89 RAND REPORT AND 7 INFORMAL DISCUSSIONS

FUNDING CONSORTIUM

DOE

DOD (E.G., USAF AND SDIO)

NSF

NIH

NASA

PRIVATE (E.G., ANTI-M AND DOD CONTRACTORS)

EUROPE (ITALY AND LEAR)

PROPOSAL

CAPTIAL: SSC OR $15 MIL. FOR BROOKHAVEN

$ 10 MIL./YR. OPERATING (AT LEAST $1 MIL./YR. FOR EACH):

(1) PRODUCTION

(2) PRODUCTION R&D

(3) TRANSPORTERS

(4) TRANSPORTER R&D

(5) "APPLIED" R&D (E.G., IMAGING, ANALYSIS & NON-PROPULSION ENERGY DEPOSITION)

PROPOSAL (CONTINUED)

(6) "ANTIGRAVITY"

(7) OTHER HENP R&D

(8) OTHER BASIC R&D ("NON-PROPULSION")

(9) PROPULSION R&D

ANTIPROTON CATALYZED FUSION

T. E. KALOGEROPOLOUS

DEPARTMENT OF PHYSICS
SYRACUSE UNIVERSITY

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

T.E.K. / BNL / 5-10-89

$\bar{P}$ CATALYSIS

$$(\bar{P}d)+d \rightarrow \bar{p}(dd)$$

$\hookrightarrow \underbrace{\text{Mesons} + 3 \text{ NUCLEONS}}_{\text{Charge} = +1}$

EXPECTED RATE (ORDER(?) ESTIMATE)

$$R_{\bar{p}}^{n} \approx \underset{10^2}{R_{\mu^-}} \cdot \underset{(10^{-11}-10^{-13})/10^{-6}}{\frac{\tau_{\bar{p}}^{n}}{\tau_{\mu^-}}} \cdot \left(\frac{r_{\mu^-}}{r_{\bar{p}}^{n}}\right)^3$$

$$\left(\frac{r_{\mu^-}}{r_{\bar{p}}^{n}}\right)^3 \rightarrow \left(\frac{m_{\bar{p}}}{m_{\mu}} \cdot \frac{1}{n^2}\right)^3 \doteq 10^3/n^6$$

For $n=2$

$$\boxed{R_{\bar{p}} \approx (1-10^{-2})\%}$$

EVIDENCE

- COMPLETE STUDY OF 3223 $\bar{P}$ ANNIHILATIONS (PRL 33, 1631, 1974) RESULTED IN SEVEN "ZOO" EVENTS

- "ZOO" EVENTS ARE NOT:

$$\bar{P} + D \longrightarrow (\bar{p}n) + P_{vis}\ (P_{inv})$$
$$\hookrightarrow \text{MESONS } (Q = -1)$$

OR

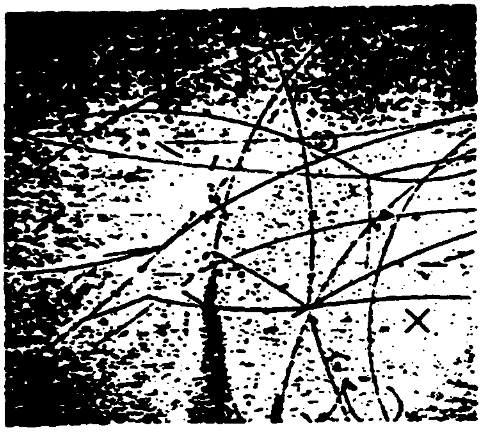
$$\longrightarrow (\bar{p}p) + n_{inv.}$$
$$\hookrightarrow \text{mesons } (Q = 0)$$

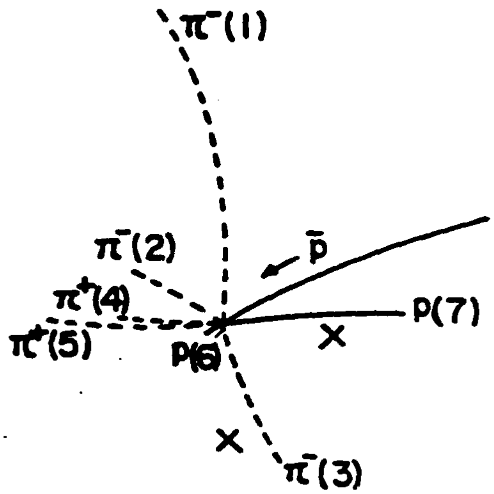
- TWO INTERESTING EVENTS

$$\bar{P} + {}^4He(dd) \longrightarrow 2P + 3\pi^- + 2\pi^+ + n$$

$$\bar{P} + X \longrightarrow 3P + 3\pi^- + 2\pi^+ + ?$$

FRAME 285126 EVENT (TWO PROTONS)

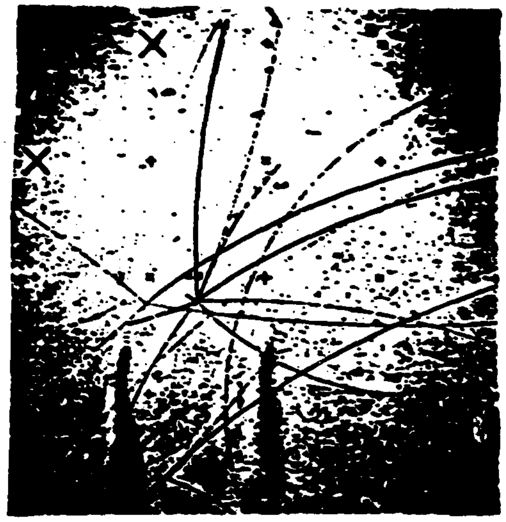


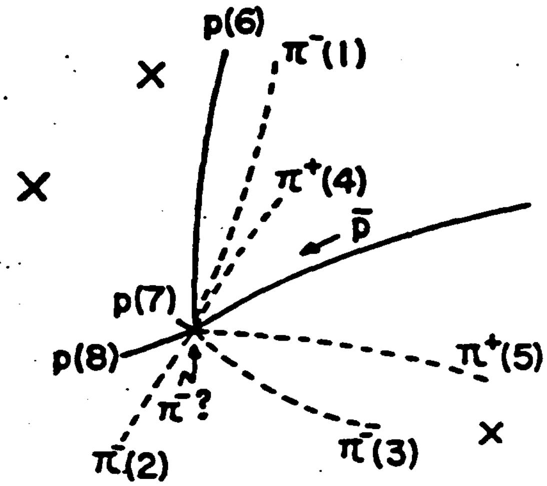


Track	θ	φ	p	P_x	P_y	P_z	E	COMMENTS
$\pi^-(1)$	-13.6±.4	42.1±3	368±26	198±14	176±13	-254±18	394±24	
$\pi^-(2)$	33.2±.2	101.6±.2	193±8	-32±1	158±7	106±4	238±6	
$\pi^-(3)$	-42.0±.4	255.6±.4	415±30	-77±6	-299±22	-278±20	438±28	
$\pi^+(4)$	-42.7±.7	1.7±.7	253±18	186±13	6±2	-172±12	289±16	
$\pi^+(5)$	53.5±.3	344.6±.4	255±15	146±9	-40±3	205±12	291±13	
P(6)	-21.0±7.3	331.2±3.9	169	139	-76	-61	958	STOPS (1.8 cm)
P(7)	50.5±.3	179.9±.3	533±35	-339±22	-1±2	411±27	1079±17	OUT (26 cm)
				221±31	-74±26	-43±42	3682±45	

$$\left.\begin{array}{l}\bar{p}+2d \rightarrow 2p+3\pi^-+2\pi^+ + MM(992\pm 48)\\ \bar{p}+{}^4He \rightarrow 2p+3\pi^-+2\pi^+ + MM(955\pm 48)\end{array}\right\} MM = m_n$$

FRAME 285082 EVENT (THREE PROTONS)





Track	ε	c	p	p_x	p_y	p_z	E	COMMENTS
$\pi^-(1)$	31.4±.1	109.4±.06	404±16	-114±5	325±13	210 ±8	428±15	
$\pi^-(2)$	-45.6±.2	301.4±.2	257±13	94±5	-154±8	-184 ±9	293±11	
$\pi^-(3)$	-33.0±.09	221.0±.06	194±7	-123±4	-107±4	-106 ±4	239±6	
$\pi^+(4)$	51.8±.16	99.7±.2	210±14	-22±2	128±9	165 ±11	252±12	
$\pi^+(5)$	10.7±.1	177.4±.05	270±7	-265±7	12±0	50 ±1	304±6	
P(6)	-30.6±.2	99.6±.1	441±15	-24±1	379±13	-224 ±8	1036±6	OUT (33cm)
P(7)	30.9±.4	26.1±.2	129.	123±1	60±1	82 ±1	952	STOPS (1.6cm)
P(8)	-34.7±.5	335.3±.4	250	187±1	-86±1	-142±2	971±0	STOPS (7.7cm)
				-144±11	557±24	-149±18	445 ±25	

$$\bar{p} + {}^4He/2d \to 3\pi^- + 2\pi^+ + 3p + MM^2 (-0.3 \pm .04\ GeV^2/c^4)$$

NOT A π!

SPECIAL SCAN FOR "ZOO" EVENTS

- FILM FROM DISTANT RUNNING PERIOD THAN THAT FOR "COMPLETE STUDY".

- TOTAL $\bar{P}$ EVENTS SCANNED 8800

  "ZOO" EVENTS FOUND 21

  $BR(ZOO) = (0.24 \pm 0.05)\%$

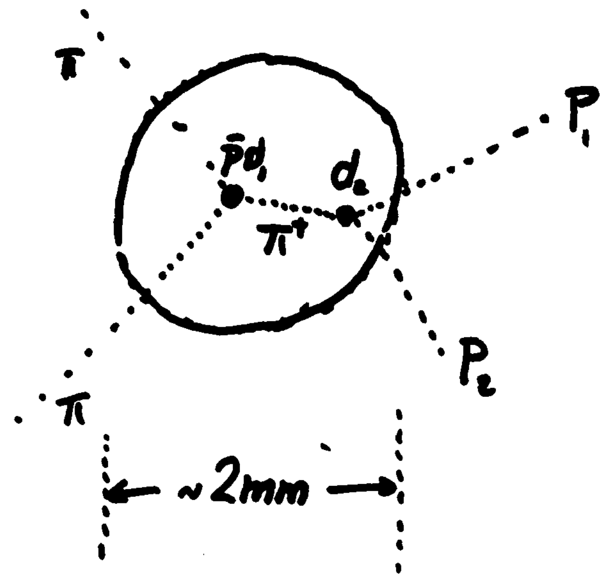
- COMPARES WELL WITH THAT OF COMPLETE SCAN:

  $BR(ZOO) = (0.22 \pm 0.08)\%$

ARE THESE EVENTS EXAMPLES OF

$\bar{P}$- FUSION CATALYSIS?

- <u>SECONDARY INTERACTIONS</u>: NO!



1) Rate of '200' events ~100 times the expected rate for secondary interactions

2) $KE(P_1) + KE(P_2) > 140\,MeV$ which is not satisfied in the two special events

- <u>CHAMBER CONTAMINANTS SUCH AS N/O</u> ...

—Typical results of chamber gas in %:

O_2 (0.05); D_2O (0.4); H_2O (0.04); HDO (0.06); N_2 (0.2).

OTHERS "UNMEASURABLE".

—BUT in D_2-liquid these contaminants should freeze out!

- WHAT ABOUT ^4He ?

— From The event which fits $\bar{p}+{}^4He$ we estimate from its a priori probability a Contamination from ^4He of ~ 10%(!)

— This is not in line with BR("200").

CONCLUSIONS

(1) $\bar{P}$-FUSION CATALYSIS IN LIQUID D_2 OCCURS WITH A RATE $\lesssim 1/100\,\bar{P}$

(2) IF POSSIBLE ^4He CONTAMINATION AT A LEVEL $\gg 1\%$ COULD BE EXCLUDED THEN A GOOD CANDIDATE EVENT FOR $\bar{P}$ D_2 FUSION INDUCED REACTION HAS BEEN OBSERVED AMONG 3000 ANNIHILATIONS.

(3) SEARCH FOR $\bar{P}$ FUSION CATALYSIS AND ITS PROPERTIES IS A GOOD COMPLIMENTARY RESEARCH TO μ^-- CATALYSIS.

ANTIPROTON INDUCED FUSION REACTION

W. S. TOOTHACKER

LABORATORY FOR ELEMENTARY PARTICLE SCIENCE
THE PENNSYLVANIA STATE UNIVERSITY
UNIVERSITY PARK, PA

Note: We regret that copies of the transparencies used in Dr Toothacker's excellent presentation were not available for inclusion in the proceedings.

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

OPTIONS FOR A LABORATORY MICROFUSION FACILITY (LMF)

BRUNO AUGENSTEIN

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PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

<u>SPECIAL DOE LABORATORY?</u>

BROOKHAVEN MEETING,
MAY 10, 1989

WORKSHOP ON ANTIPROTON TECHNOLOGY

RAND

Bruno Augenstein May 2, 1989—1

DOE LABORATORY MICROFUSION FACILITY (LMF) FOR TESTING

- Valid operational requirement
- Why have an LMF?
  - — Simulate underground explosions in laboratory setting
- Against what contingencies?
  - — Nuclear test ban: complete, or more restricted than current limitations
- No "assured design" yet for meeting LMF requirements

RAND

RAND Vugraphs PC May 2, 1989—2

WHAT CAN DO WE DO WITH AN LMF?

- Maintain nuclear design competence (complement, validate computations)— ideally, with many tests per year
  - — Equation of state; opacity; energy flows; design principles
  - — Exploratory research on new concepts
  - — Effects simulation
- "Laboratory" facility → maximum energy releases in ~1/10 - 1 ton HE range
- Keep core proficiency program going
  - — Prevent technological surprise, breakout

RAND

TWO OPTIONS FOR LMF

CONCEPTUAL STAGE (DOE)

- Very high energy laser, particle beam
  - — Ignite small TN pellet
- TN energy release
  - — 200-1000 MJoules
- Effects simulation
  - — Radiation, EMP, etc.
- Projected cost goals
  - — $700 to 1000 million
- Construction projections
  - — 5-6 years?
  - — Available late 90s?

ALTERNATIVE POSSIBILITY

- Use antiproton source
  - — Based on J. Solem paper ('87 Proceedings)
  - — Additional classified paper (Solem, Mayer, Augenstein)
  - — Other related aspects (Pennsylvania State Group - G. Smith, et al)

(Both options have two distinct regimes:
1. Ignite fuel, very local region;
2. Conditions for sustained propagation of ignition.
2. >> 1. in experimental preparations)

RAND

RAND Vugraphs PC May 2, 1989—4

ANTIPROTON OPTION FOR LMF

- Initial experimentation
  - — Standard initial tools
    - Antiproton source (~10^{14} - 10^{16} antiprotons/year) – use a small fraction
    - Portable storage
  - — Significant Technical issues
    - Space/time compression of antiproton bunch; target configuration; precision diagnostics (much death by normal matter effects.)
    - Parameterized by Solem; Pennsylvania State group
- Broad-scale experimentation (comparable to laser, PB option plans)
  - — Source roughly equivalent to Large Hadron Facility capability
  - — Progress in storage, extraction, post-extraction compression

RAND

RAND Vugraphs PC May 2, 1989—5

LMF RECOMMENDATIONS

- DOE sponsor <u>serious look</u> at antiproton option
  - Comparable ground rules to laser, PB option
- Two cost bases
  - <u>Piggy-back</u> on Large Hadron Facility source, if firmed up; or,
  - <u>Stand-alone source</u> comparable to Large Hadron Facility source
- Evaluate range of simulation experimentation possible
  - Availability for other kinds of experimental uses

(fac. for LMF allows basic science expts. and expts. in other fields — e.g., propulsion, power generation)

- Criteria for antiproton option viability (initial screening)
  - Comparable range of uses
  - Highest cost option (stand-alone source) ≤ laser, PB projections

(reason for belief von highest cost much less than laser, PB costs)

RAND

RAND Vugraphs PC May 2, 1989—6

MODELING ANTIPROTON - PLASMA INTERACTIONS

(ANTIMATTER THRUSTER MODELING)

JOHN L. CALLAS

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HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

Antimatter for Spacecraft Propulsion

ANTIMATTER THRUSTER MODELING

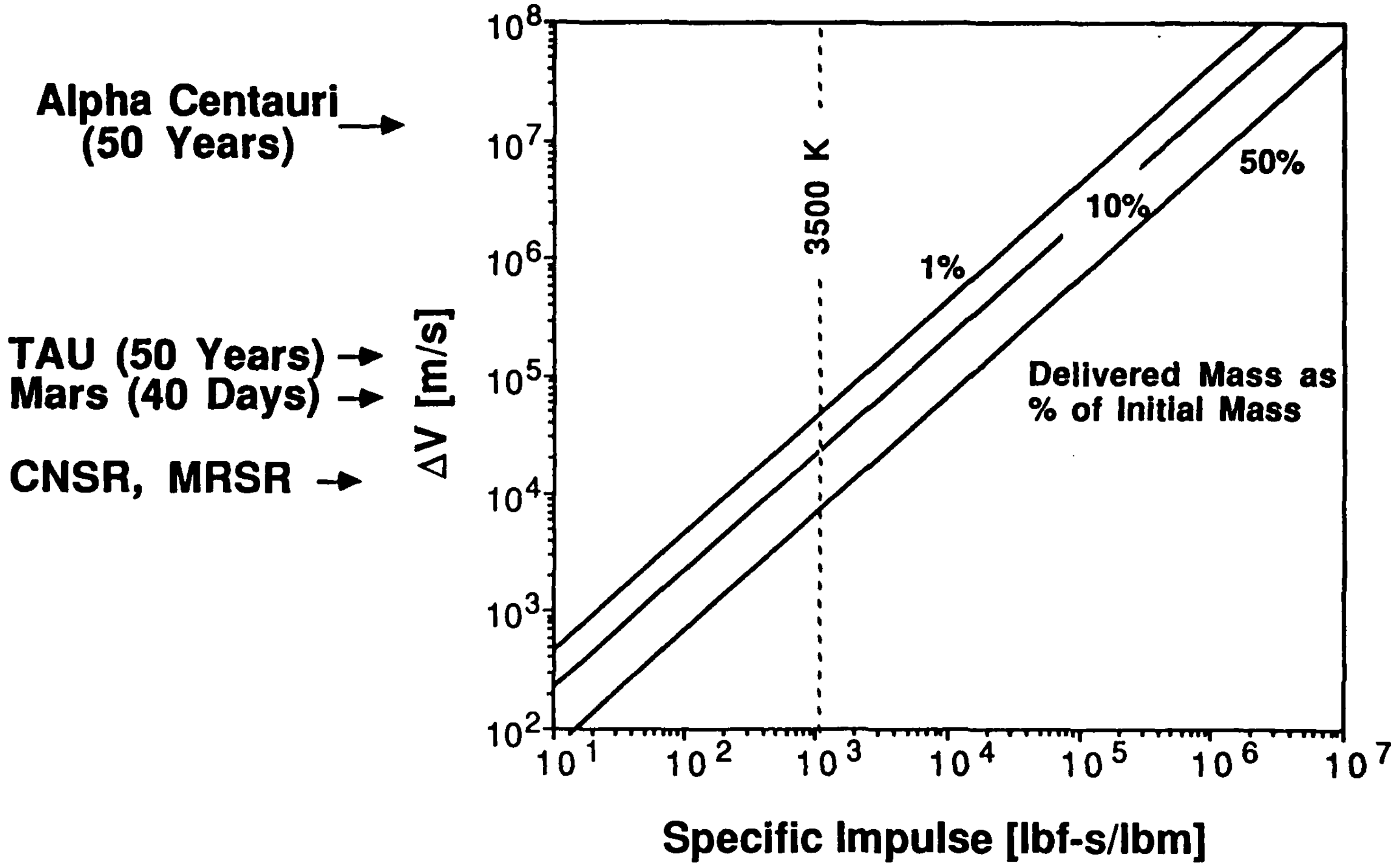
JPL

JOHN L. CALLAS

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

JPL

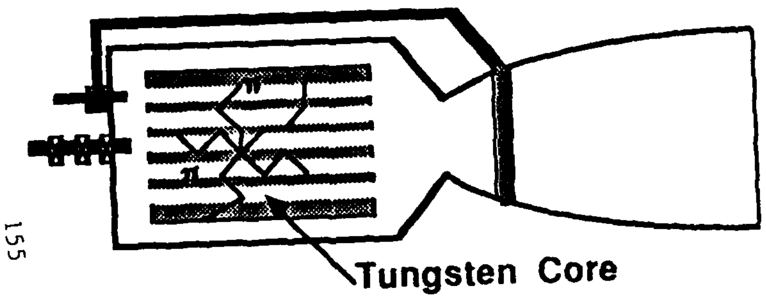
MISSION ΔV vs SPECIFIC IMPULSE



ANTIMATTER THRUSTER CONCEPTS

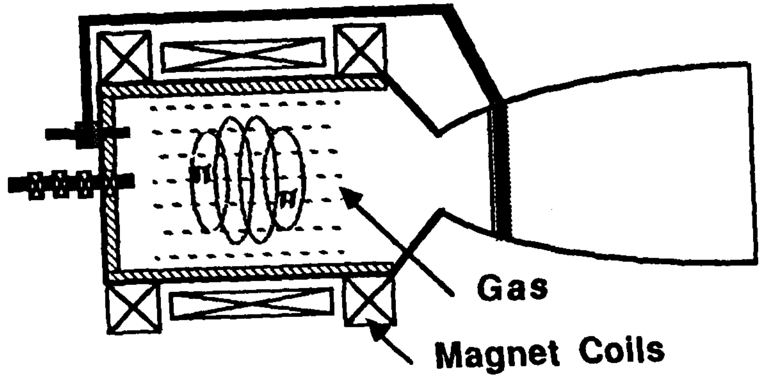
SOLID CORE

Isp = 800-1000 lbf-s/lbm
Efficiency < 70%



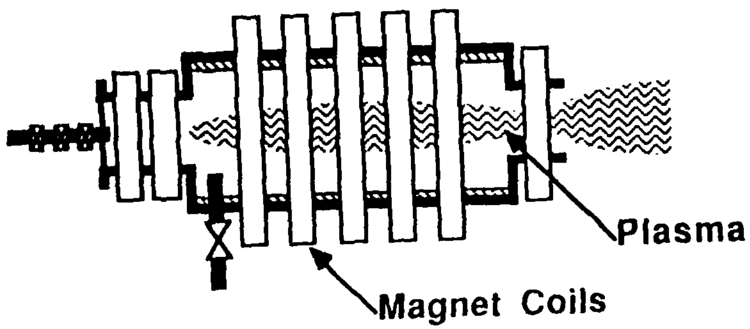
GAS CORE

Isp = 1000-2500 lbf-s/lbm
Efficiency < 50%



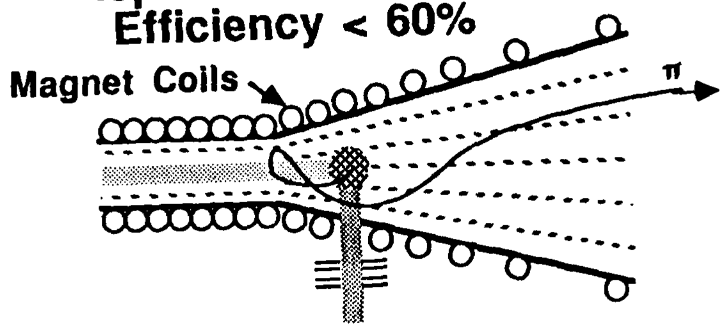
PLASMA CORE

Isp = 5000-100000 lbf-s/lbm
Efficiency << 50%



BEAM CORE

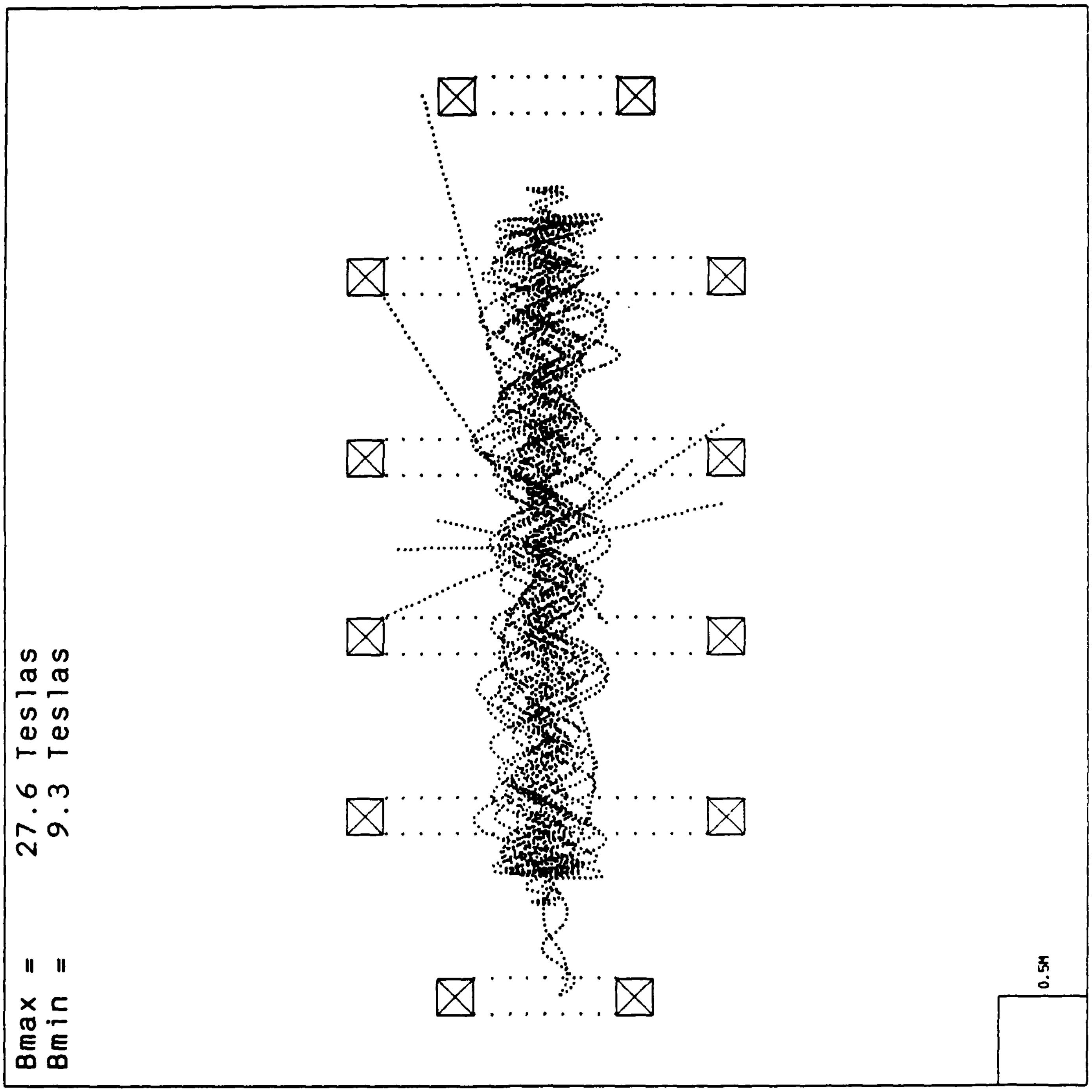
Isp = 10^7 lbf-s/lbm
Efficiency < 60%



JPL

ANTIMATTER THRUSTER ISSUES

- dE/dx in Plasmas
- Photon Attenuation
- Bremsstrahlung Radiation (Electrons, Plasma)
- Synchrotron Radiation (Electron, Plasma)
- Nuclear Processes (Charge Exchange, Fission)
- Particle Decays (Neutrino Losses)
- Confinement (Annihilation Products, Plasma)
- Technology (Magnets, Shielding)



Bmax = 27.6 Teslas
Bmin = 9.3 Teslas
0.5M

JPL PRELIMINARY MODELING RESULTS

- Very Low Efficiency (<1%)
- Ultra High Loss Mechanisms (Neutrinos, Bremsstrahlung)
- Poor Annihilation Product Confinement (Charged and Neutral)
- Very Challenging Technology (Magnets, Shielding)

CONCEPTS FOR THE EXPERIMENTAL DETERMINATION OF RADIATION SHIELDING AND METAL CLAD PELLET PERFORMANCE

BRICE CASSENTI

UNITED TECHNOLOGIES RESEARCH CENTER
HARTFORD, CT

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

Concepts for the Experimental Determination of Radiation Shielding and Metal Clad Pellet Performance

Brice Cassenti

UNITED TECHNOLOGIES RESEARCH CENTER

RADIATION SOURCE

- **Annihilation reaction**

$$p + \bar{p} \longrightarrow n\pi^{+} + n\pi^{-} + m\pi^{\circ}$$

- **Neutral pion decay**

$$\pi^{\circ} \longrightarrow \gamma + \gamma$$

RA2197TX.016

Additional Radiation Sources

- **Charge Exchange**

$$\pi^- + p \longrightarrow n + \pi^0$$

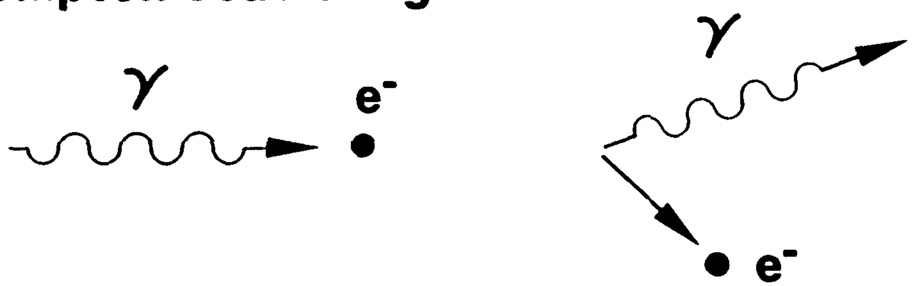
- **Fission**

$$\pi + Z \longrightarrow Z_1 + Z_2 + kn$$

- **Etc.**

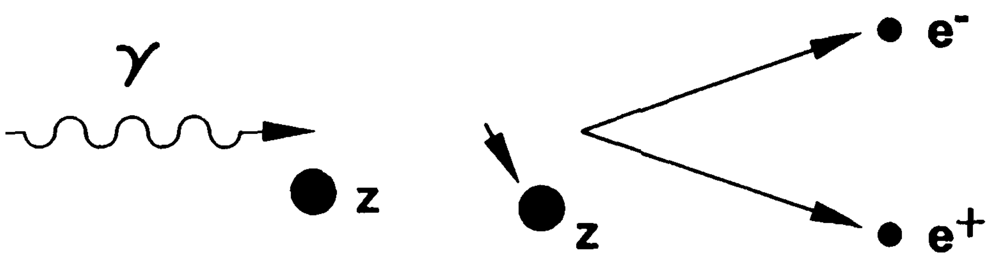
GAMMA RAY INTERACTIONS

- **Compton scattering**



$$\gamma + e^- \longrightarrow \gamma + e^-$$

- **Pair creation**



$$\gamma \xrightarrow{z} e^+ + e^-$$

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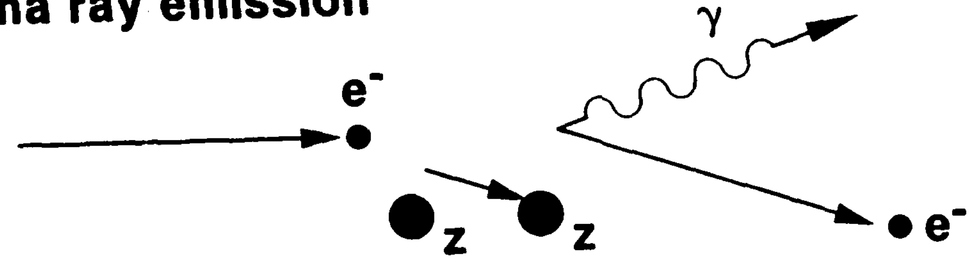
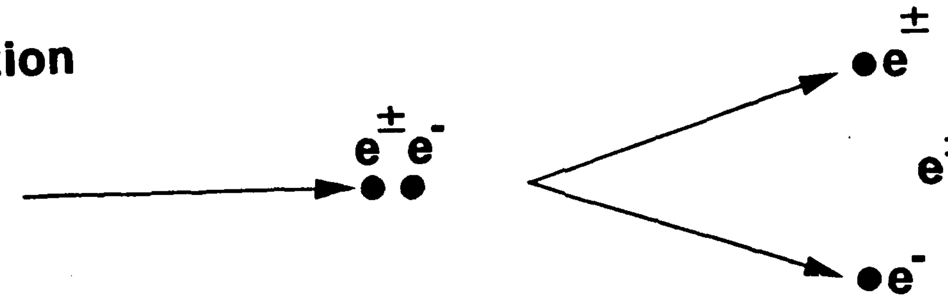
ELECTRON / POSITRON INTERACTIONS

- Gamma ray emission



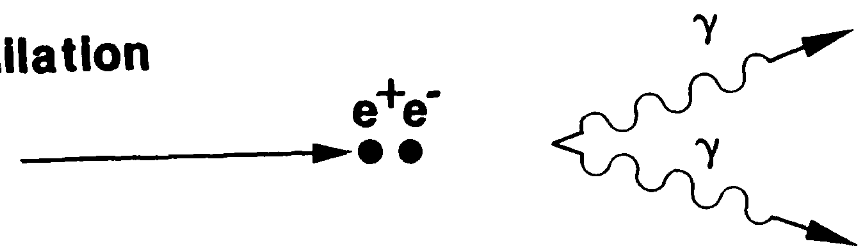
$e^- \xrightarrow{Z} \gamma + e^-$

- Ionization



$e^\pm + e^- \longrightarrow e^\pm + e^-$

- Annihilation



$e^\pm + e^- \longrightarrow \gamma + \gamma$

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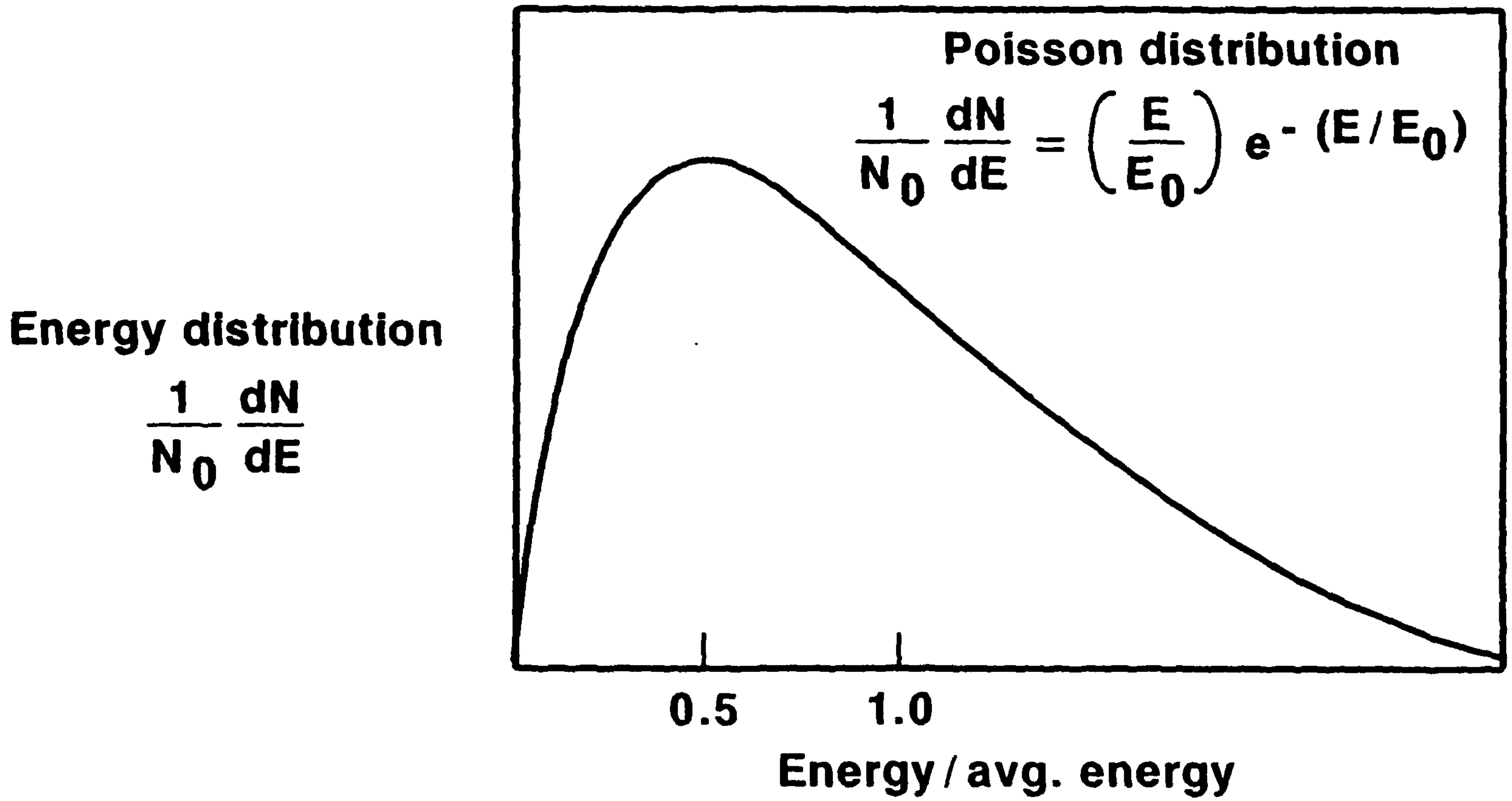
GAMMA RAY ENERGY DISTRIBUTION



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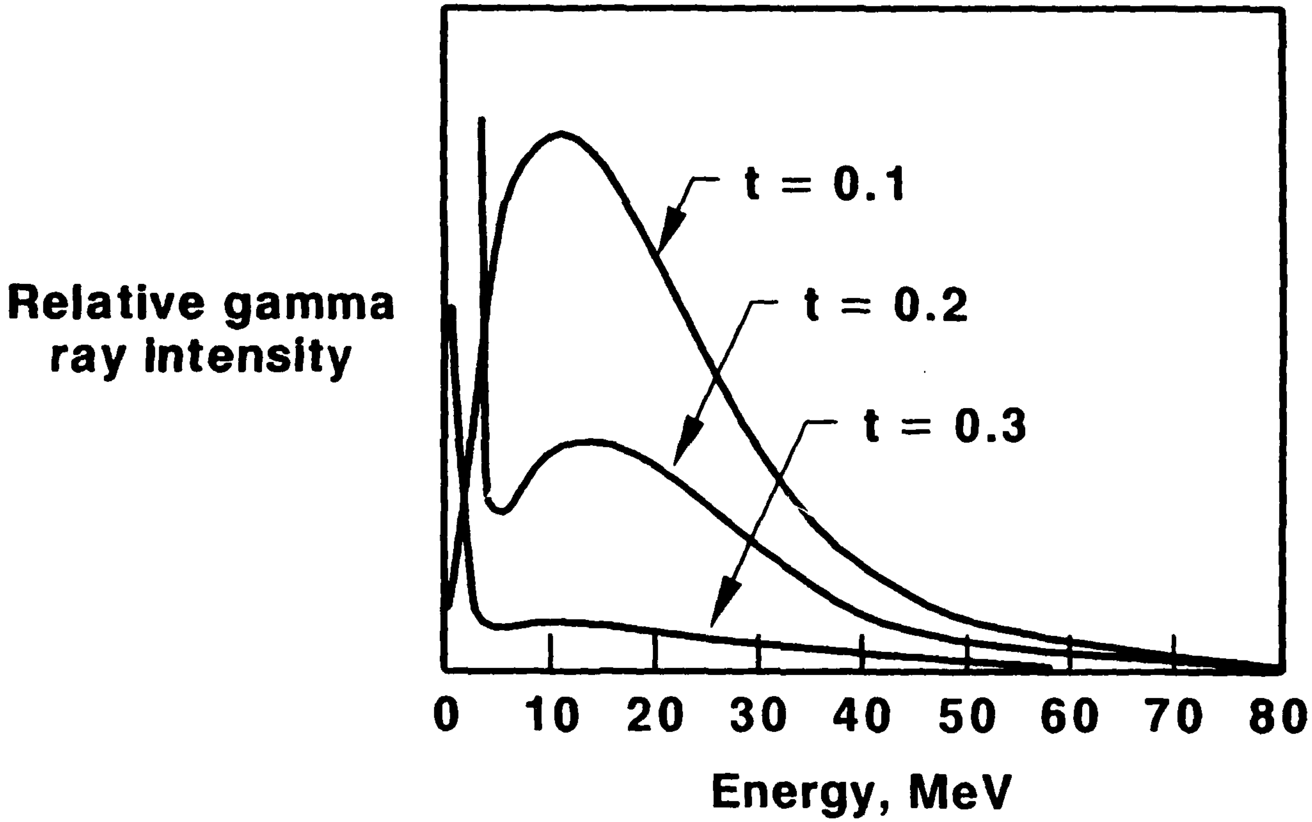
GAMMA RAY INTENSITY VARIATION

- Tungsten
- π° decay



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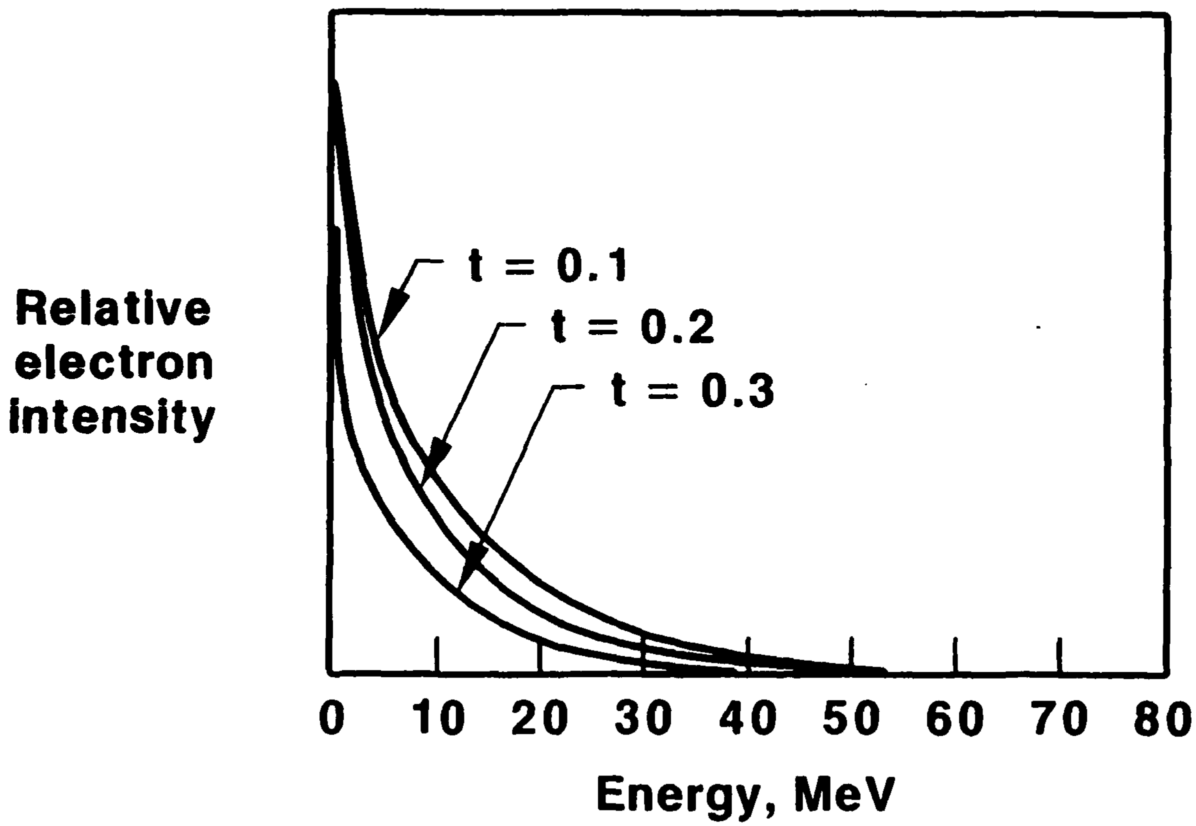
ELECTRON / POSITRON INTENSITY

- Tungsten
- π° decay



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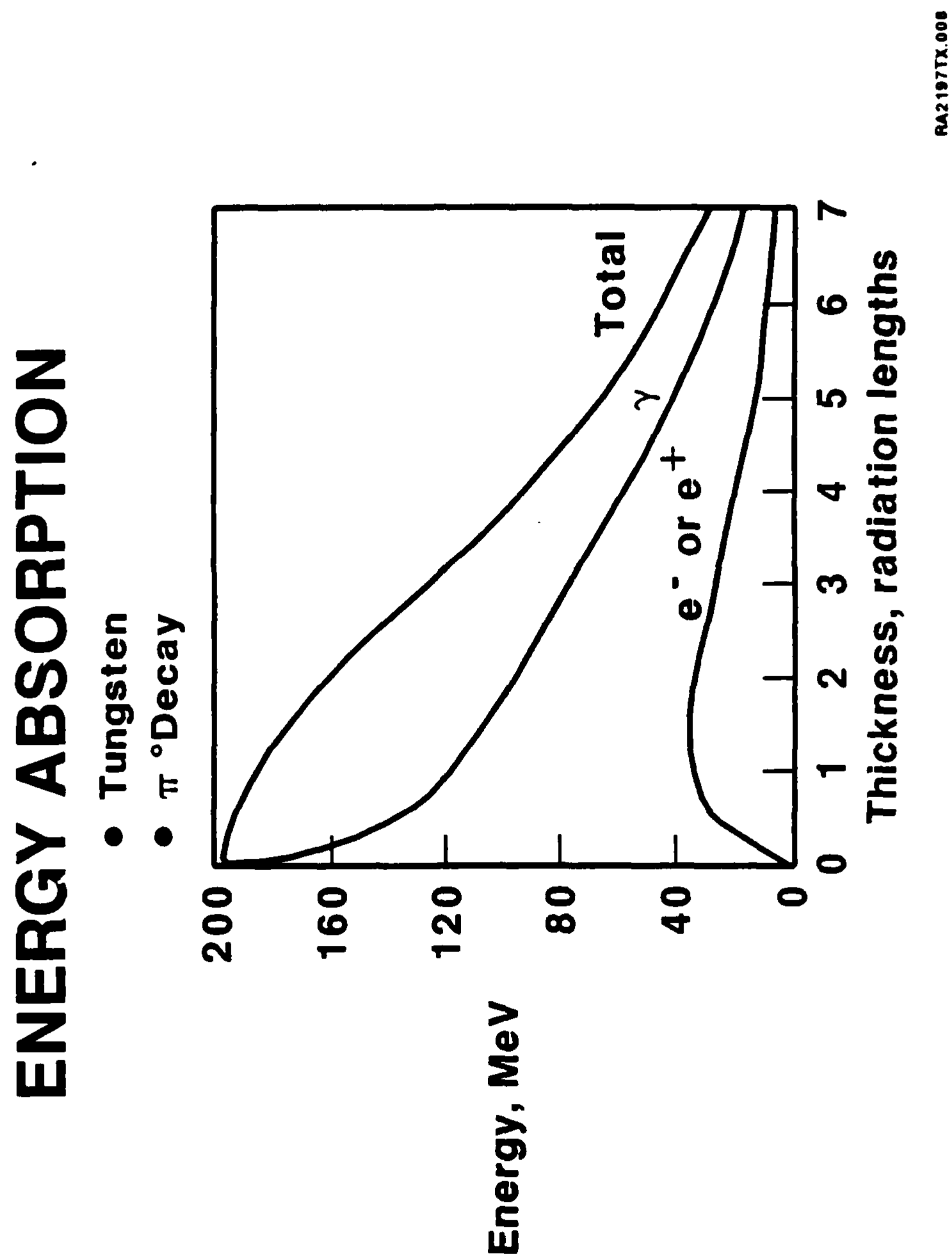


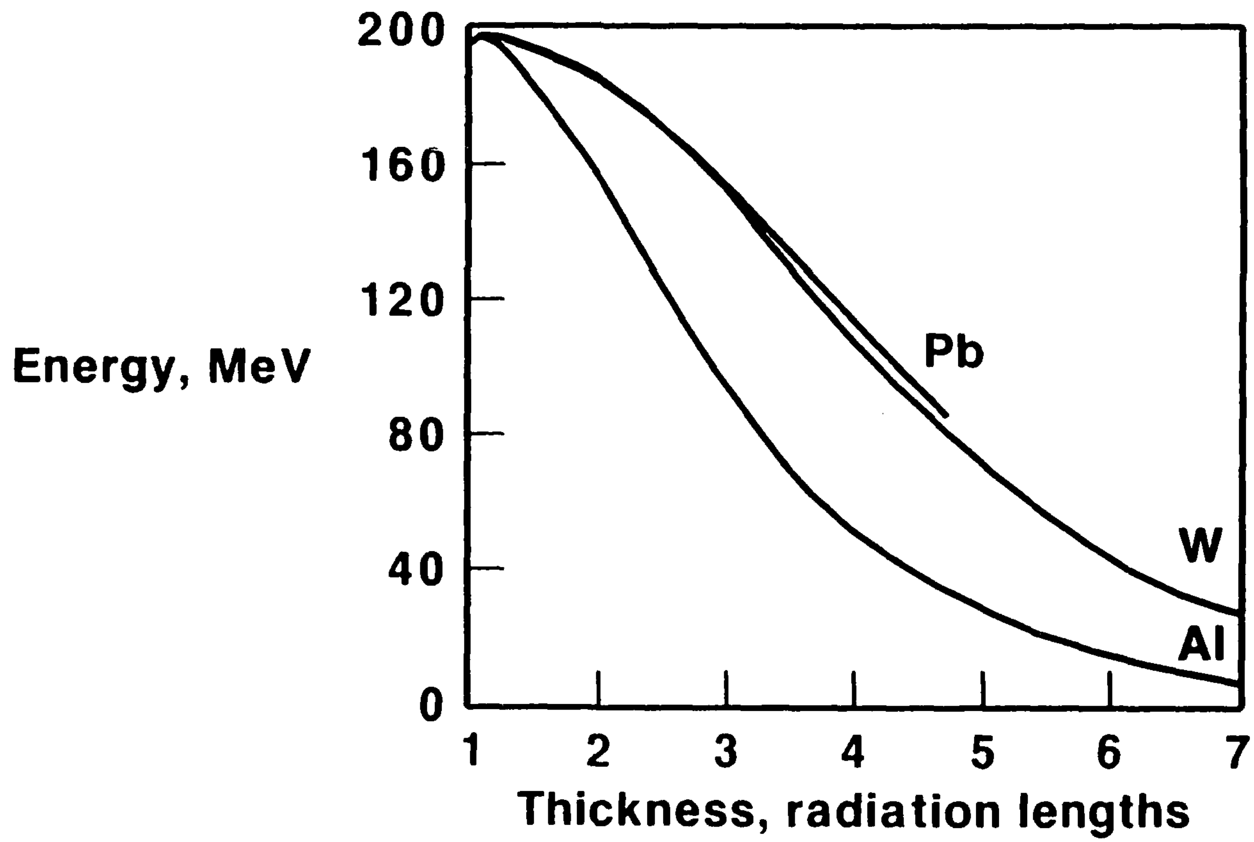
(3)

Enabling procedure (Donoghue, 1986)

$\bar{p}p \to \bar{\Xi}\Xi$

ENERGY ABSORPTION

- π°Decay



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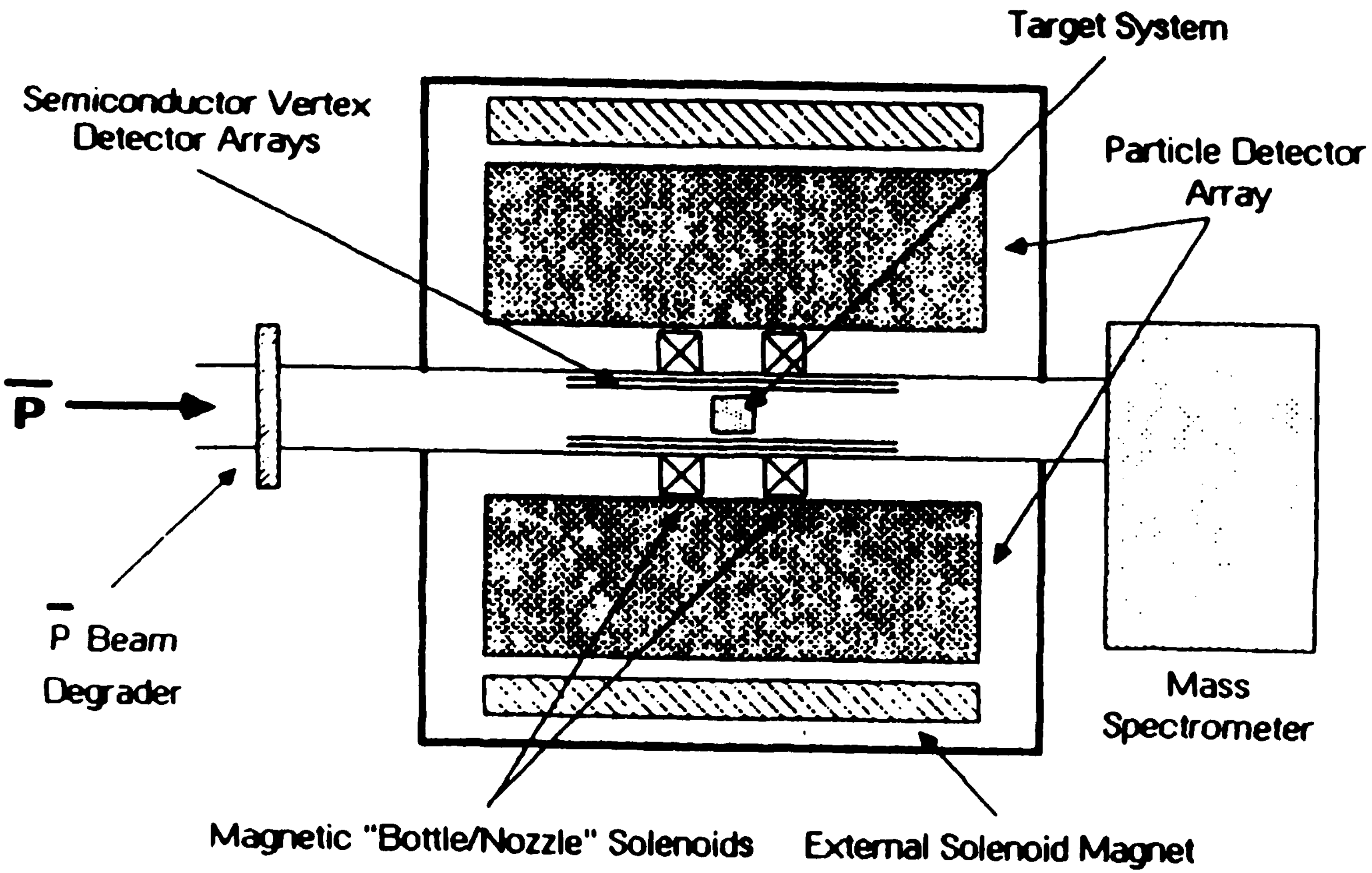
SAMPLE CALCULATION

- OTV mission
  - 10 ton payload
  - 5.5 km/s velocity increment
  - 8 mg annihilated
- Shield mass
  - 3.5 tons
- Maximum temperature rise
  - 500 deg C

RA2197TX.017

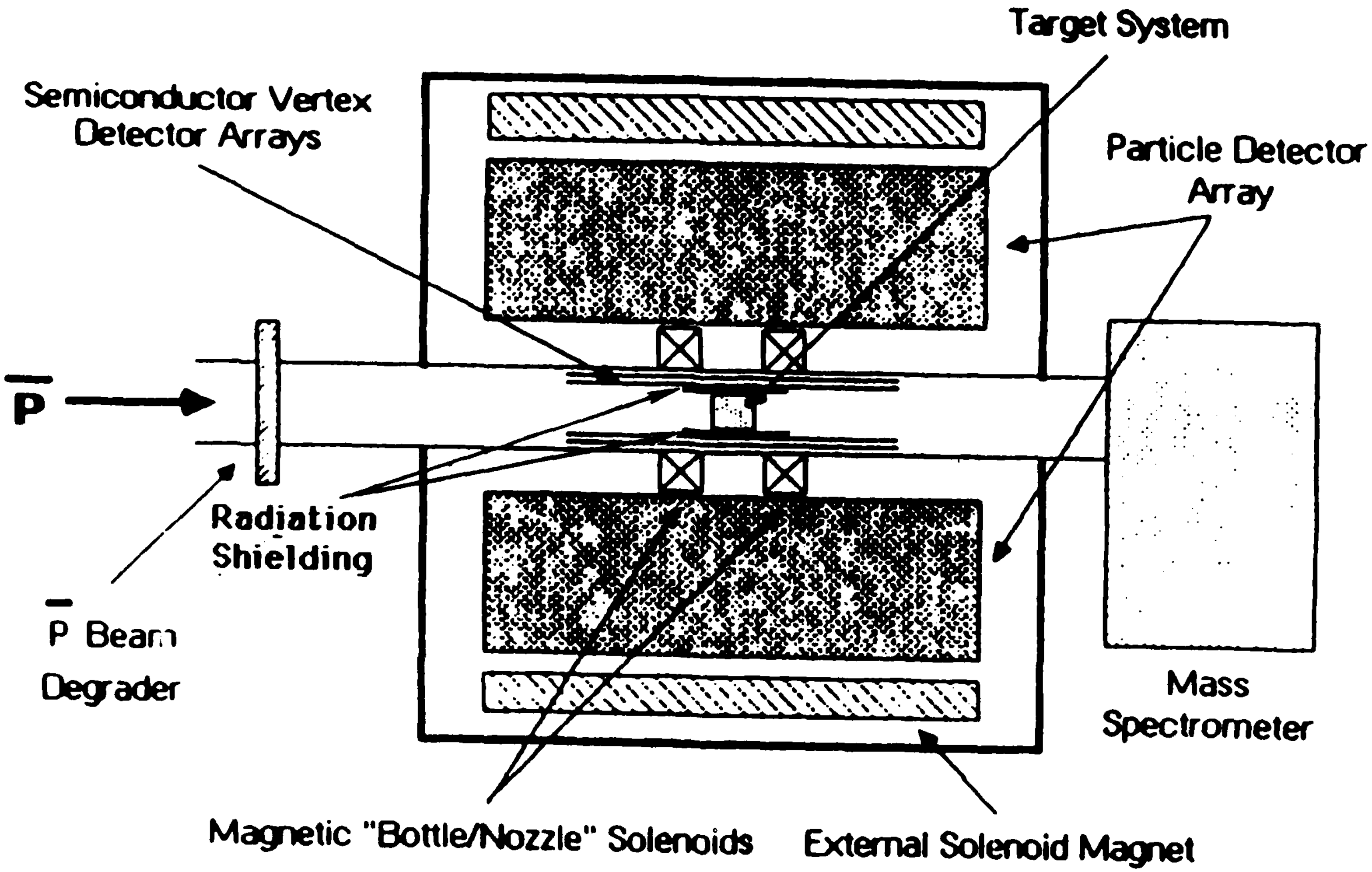
JPL

ANTIMATTER INTERACTION EXPERIMENT



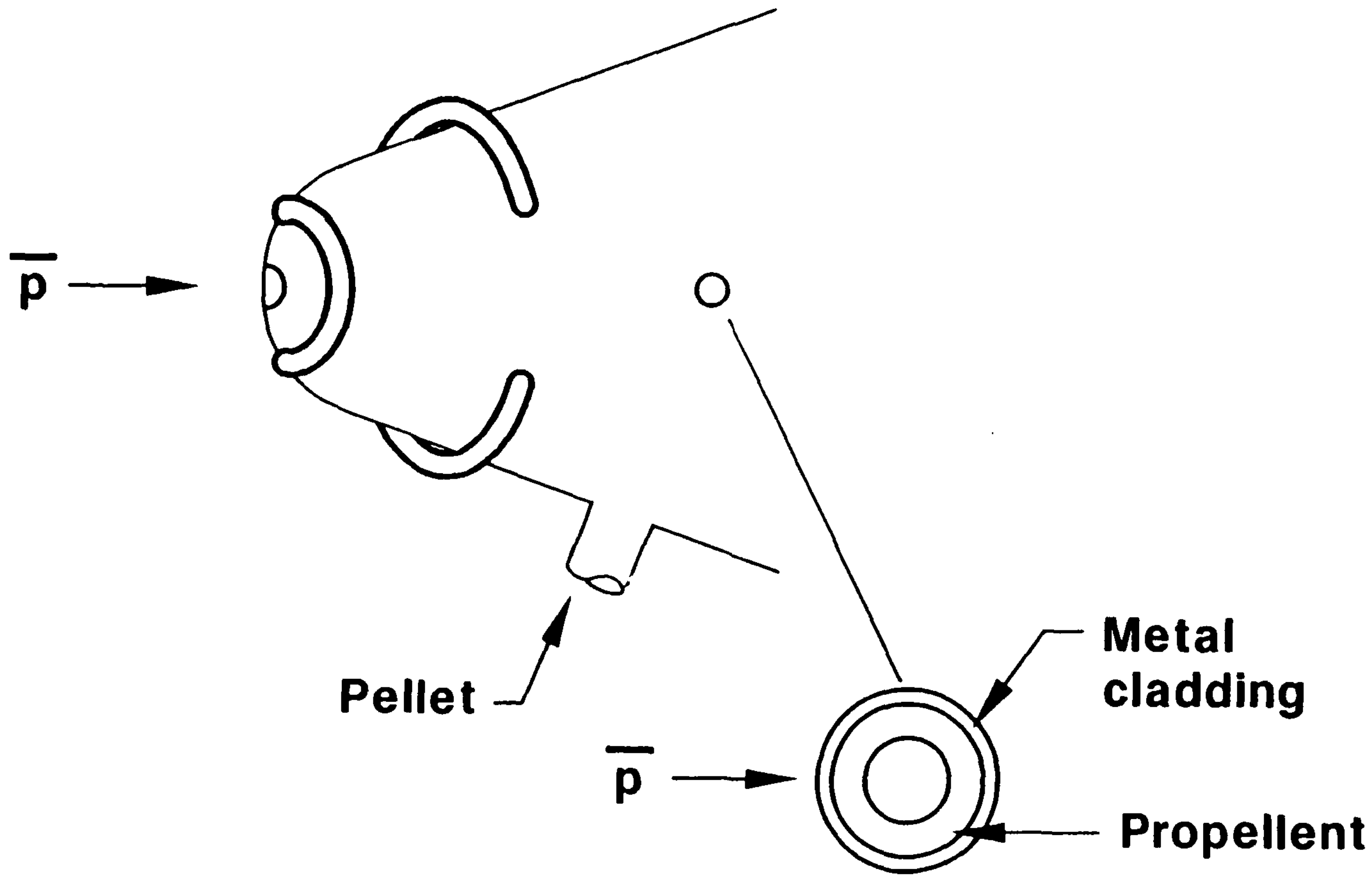
from Callas: Antimatter Spacecraft Propulsion Experiments...

JPL ANTIMATTER INTERACTION EXPERIMENT



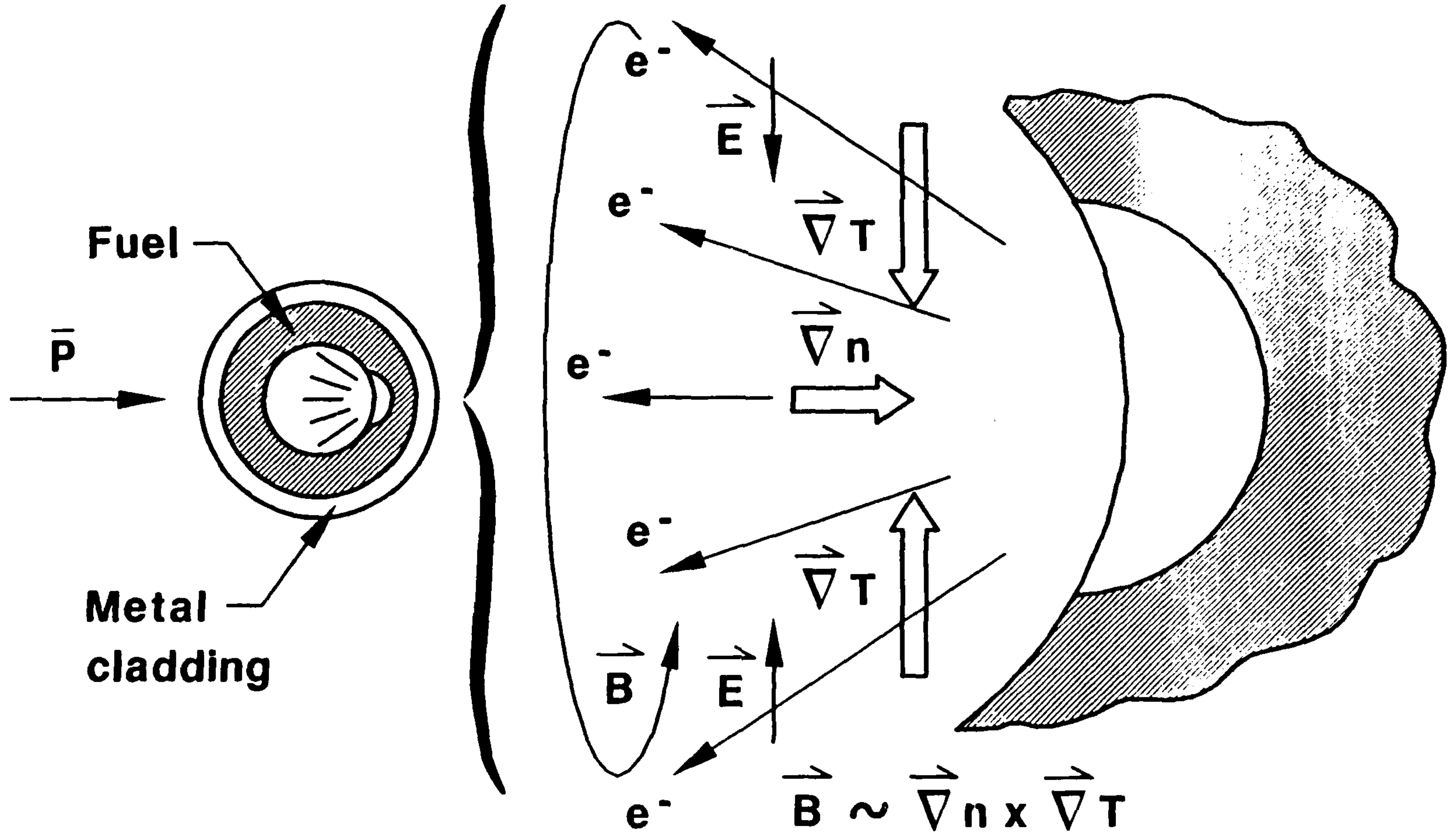
from Callas: Antimatter Spacecraft Propulsion Experiments...

PELLET ROCKET CONCEPTUAL DESIGN



RA3008TX.004

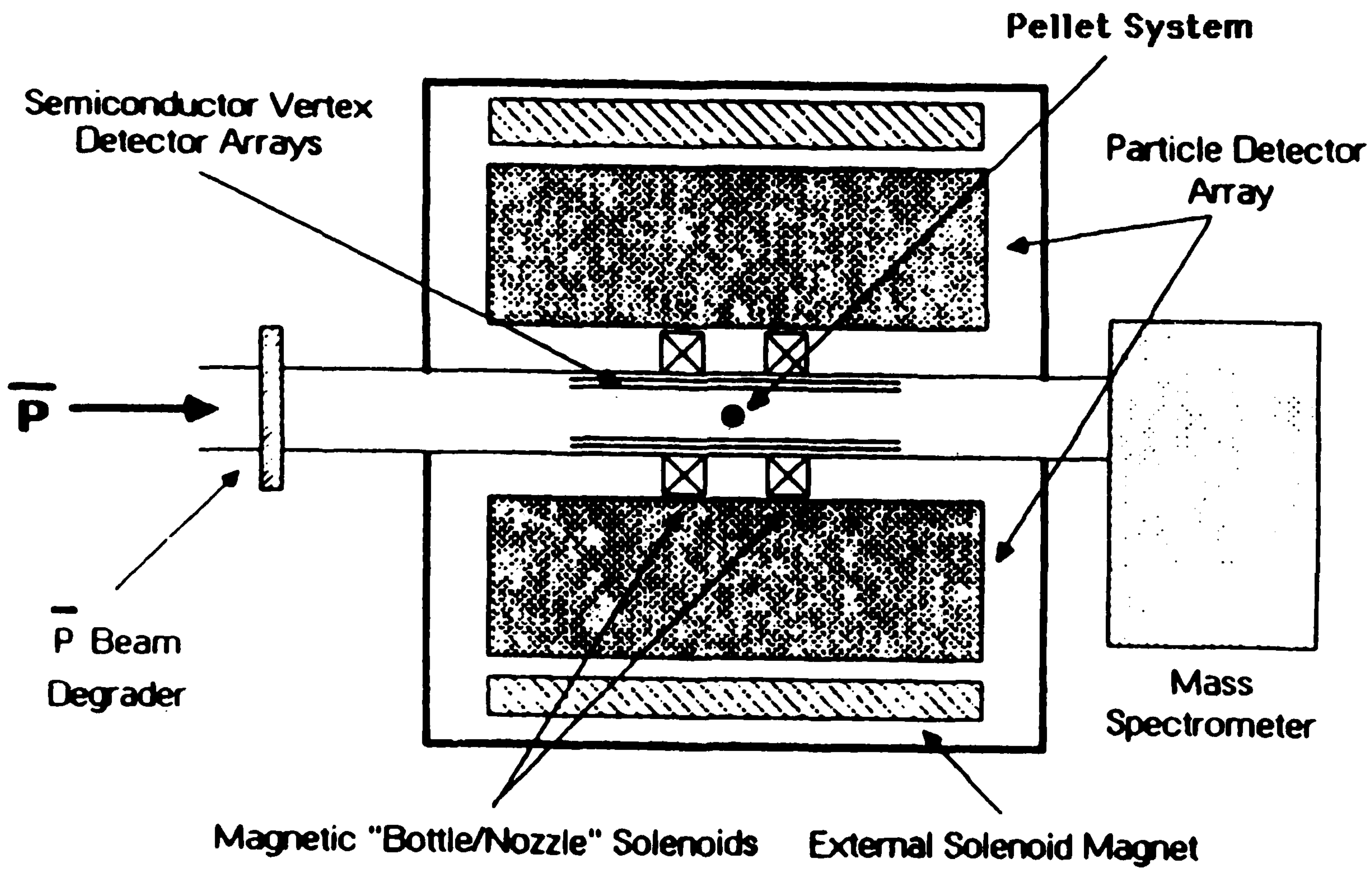
PELLET CONTAINEMENT



RA199TX.012

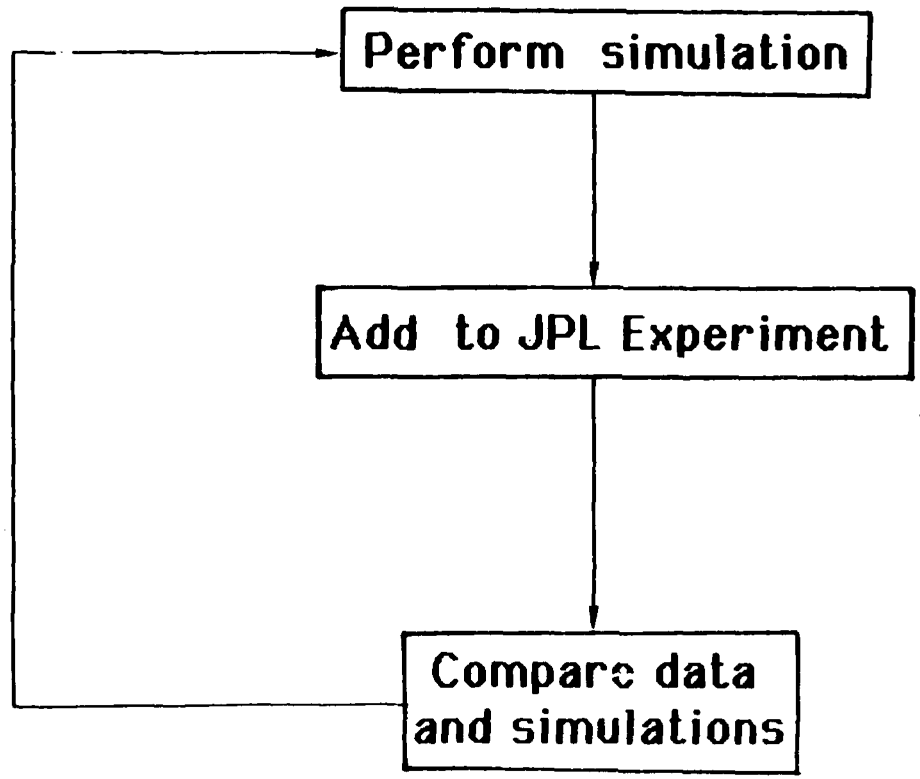
JPL

ANTIMATTER INTERACTION EXPERIMENT



from Callas: Antimatter Spacecraft Propulsion Experiments...

PROGRAM OUTLINES



Summary

- Radiation shielding
- Pellet performance
- JPL Experiment
- Simulations

References

Cassenti, B. N.: Radiation Shield Analysis for Antimatter Rockets. Paper No. AIAA-87-1813, presented at the AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego, June 29–July 2, 1987.

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Max, C. E., W. M. Manheimer and J. J. Thomson: Enhanced Transport Across Laser Generated Magnetic Fields. Phys. Fluids, Vol. 21, pp 128–139, 1978.

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Kammash, T. and D. L. Galbraith: Mars Missions with the MICF Fusion Propulsion System. Paper No. AIAA-88-2926, presented at the AIAA/ASME/ASEE 24th Joint Propulsion Conference, Boston, July 11–13, 1988.

INTRODUCTION TO CP VIOLATION STUDIES WITH Pbars

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HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

CP Violation

Kaon decay (Fitch + Cronin, 1964)

$$K_S \to 2\pi, \quad K_L \to 3\pi, \quad \Gamma_L \sim .002\,\Gamma_S$$

Limitations:

1) Two parameters only, ϵ and ϵ'.
No other $\not{CP}$ in (u, d, s) at present.

2) Fundamental question unresolved:

i) $|\Delta S| = 2$ only (superweak)

ii) $\begin{cases} |\Delta S| = 1 & \text{(milliweak)} \\ \text{and } |\Delta S| = 2 & \text{by second-order} \end{cases}$

(2)

Hadron decay (T.D. Lee, 1966; Overseth + Pakvasa, 1969)

Non-leptonic,

$$\Xi^- \to \pi^- + \Lambda$$
$$\qquad\qquad \hookrightarrow \pi^- + p$$

vs.

$$\bar{\Xi}^+ \to \pi^+ + \bar{\Lambda}$$
$$\qquad\qquad \hookrightarrow \pi^+ + \bar{p}$$

Compare: decay rate, $\Gamma - \bar{\Gamma}$

$\alpha(\vec{\sigma}\cdot\vec{p})$, $\alpha + \bar{\alpha}$

$\beta(\vec{\sigma}\times\vec{\sigma}'\cdot\vec{p})$, $\beta + \bar{\beta}$

In principle, 3 new measures of $\cancel{CP}$

$\Longrightarrow$ All are $|\Delta S| = 1$

Enabling procedure (Donoghue, 1986)

$$\bar{p}p \to \bar{\Xi}\,\Xi$$
$$\to \bar{\Lambda}\,\Lambda$$

Production: strong interaction, preserves CP

$\therefore$ Perfect anticorrelation of initial states,

$$\underset{\sim}{\sigma} = -\underset{\sim}{\bar{\sigma}}, \qquad \underset{\sim}{p} = -\underset{\sim}{p}$$

Eliminates major uncertainties.

Estimates for K-M, Higgs, Left-right:

$\underline{\Xi \to \pi\,\Lambda}$

$$|\beta + \bar{\beta}| \sim 10^{-4} \text{ to } 10^{-3} \sim 3|\alpha + \bar{\alpha}|$$

$\underline{\Lambda \to \pi\,p}$

$$|\beta + \bar{\beta}| \sim 10^{-4} \text{ to } 10^{-3} \sim 7|\alpha + \bar{\alpha}|$$

(4)

Implementation

1) Don't attempt $(\Gamma-\bar{\Gamma})/(\Gamma+\bar{\Gamma}) \sim 10^{-6}$ to 10^{-5}

2) $|\alpha+\bar{\alpha}|_\Lambda < |\alpha+\bar{\alpha}|_\Xi$ (estimate)

3) $|\beta+\bar{\beta}|_\Xi$ only feasible. Λ decay analyzes $\underset{\sim}{\sigma}'$

Conflicting aims:

i) $\sigma_{\Lambda\bar{\Lambda}} \sim 10\,\sigma_{\Xi\bar{\Xi}}$, but CP parameters largest (estimated) for $\Xi\bar{\Xi}$.

ii) For $\Xi\bar{\Xi}$, $|\beta+\bar{\beta}| > |\alpha+\bar{\alpha}|$; but $|\alpha+\bar{\alpha}|$ simpler, perhaps higher acceptance.

TEST OF NON-CONSERVATION IN

IN P bar-P to Ξ bar - Ξ

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Note: We regret that reproducible copies of the transparencies used in Dr Nathan's excellent presentation were not available for inclusion in the proceedings.

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
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10 MAY 1989

STUDIES OF CP VIOLATION WITH PURE K_O - K_O bar BEAMS FROM P bars

JAMES MILLER

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Note: We regret that reproducible copies of the transparencies used in Dr Miller's excellent presentation were not available for inclusion in the proceedings.

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10 MAY 1989

SEARCH FOR CP VIOLATION IN

Pbar P –> J/Ψ –> Λ^0 Λ^0bar

G. A. SMITH

LABORATORY FOR ELEMENTARY PARTICLE SCIENCE
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UNIVERSITY PARK, PA

PRESENTED AT THE ANTIPROTON TECHNOLOGY WORKSHOP
HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

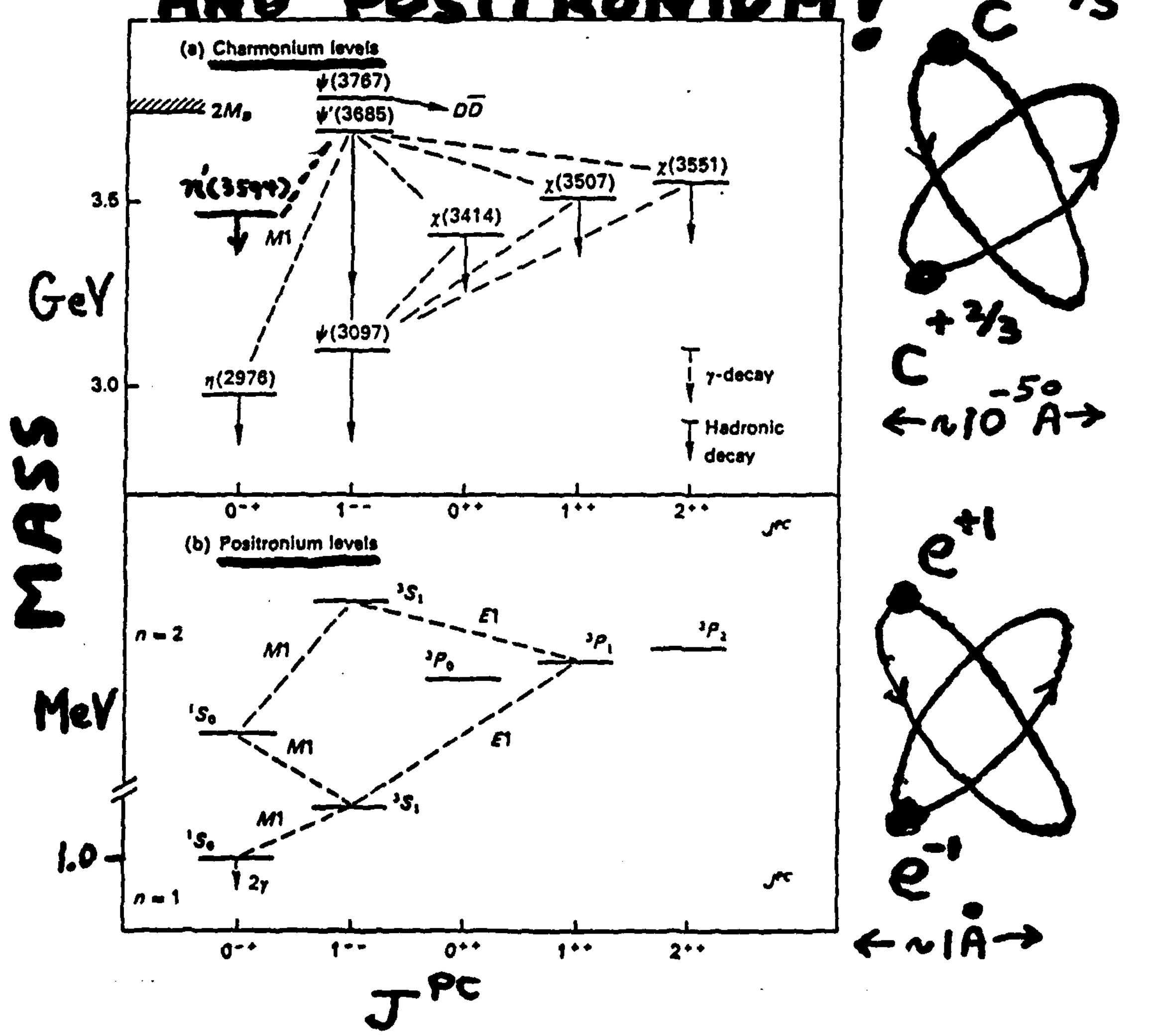
SEARCH FOR CP-VIOLATION IN $\bar{P}P \rightarrow J/\psi \rightarrow \Lambda^{\circ}\overline{\Lambda^{\circ}}$

G.A. SMITH
(PENN STATE)

WORKSHOP
ON
ANTIPROTON TECHNOLOGY
MAY 10, 1989
BNL

HIGH RESOLUTION HEAVY QUARK SPECTROSCOPY WITH ANTIPROTONS

NOTE REMARKABLE SIMILARITY BETWEEN SPECTRA OF CHARMONIUM AND POSITRONIUM!



R704 (ISR)

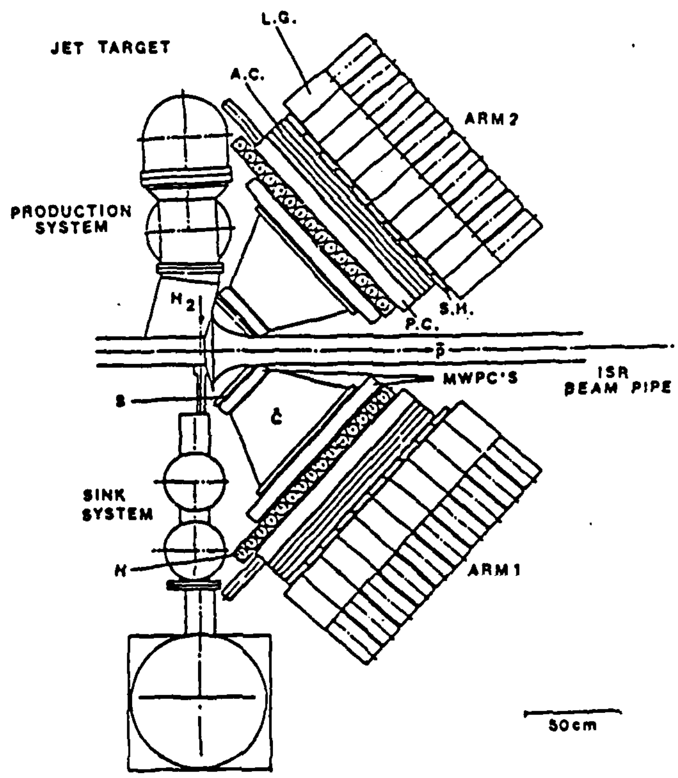


Table 2
$\bar{p}p \to J/\Psi \to e^+e^-$ runs

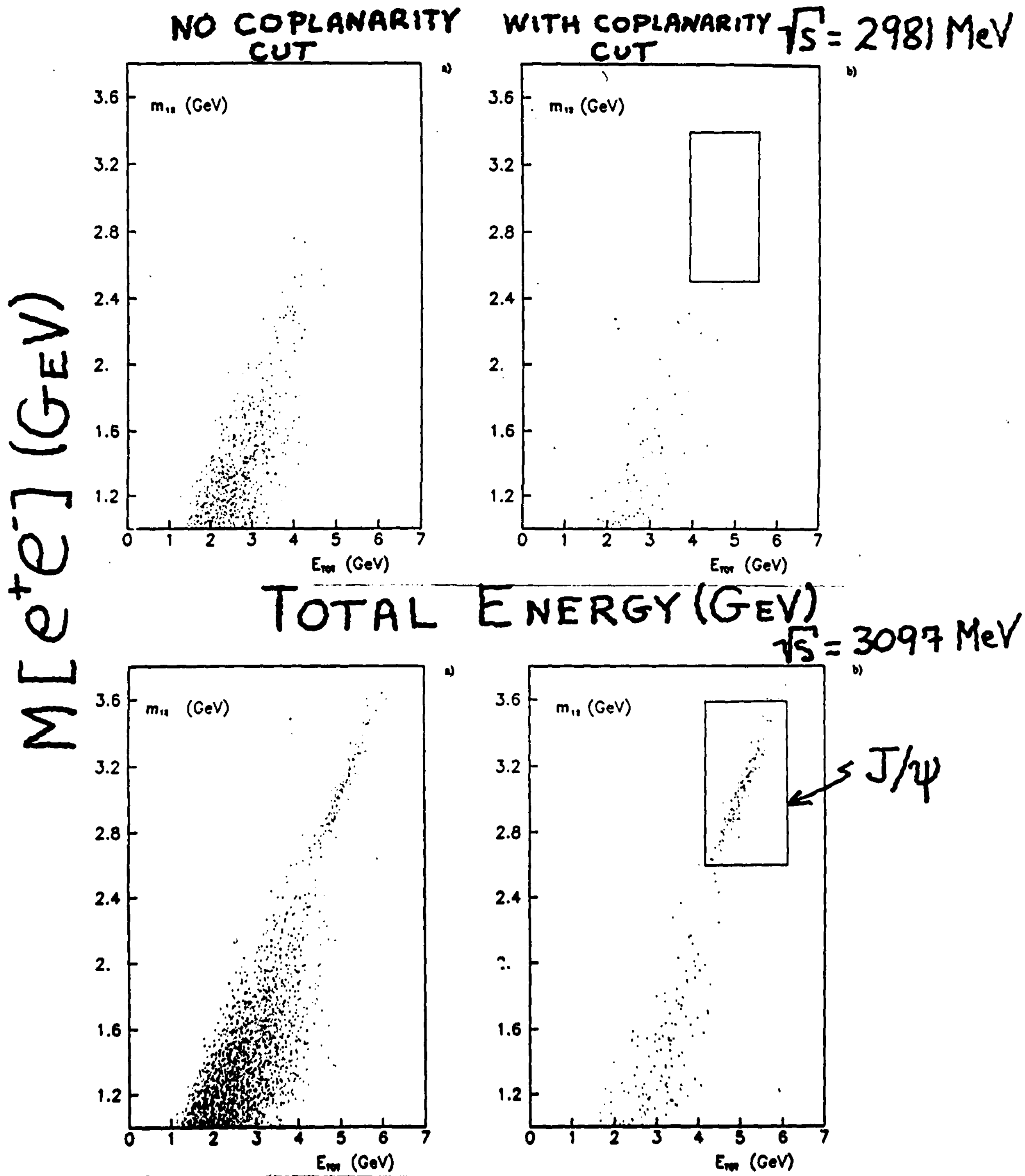
$\bar{p}p \to J/\psi \to e^+e^-$

Run	Date	$\sqrt{s}$ (MeV/c^2)	$\int L\,dt$ (nb^{-1})	Events	Mass (MeV/c^2)
1	11 May 1983	3096.7–3101.0	10.0	16	$3097.05^{+0.22}_{-0.21}$
2	19 July 1983	3095.8–3097.5	8.0	13	$3097.35^{+0.22}_{-0.30}$
3	26 July 1983	3096.4–3097.6	18.0	14	$3095.69^{+0.36}_{-0.32}$
4	3 August 1983	3096.4–3097.0	21.5	34	$3096.66^{+0.25}_{-0.19}$
5	22 March 1984	3096.1–3098.0	63.5	81	$3096.79^{+0.14}_{-0.11}$
6	5 April 1984	3096.7	20.0	35	$3096.64^{+0.34}_{-0.64}$

C. Baglin et al, Nucl. Phys. B286, 592 (1987)

R704 (ISR)

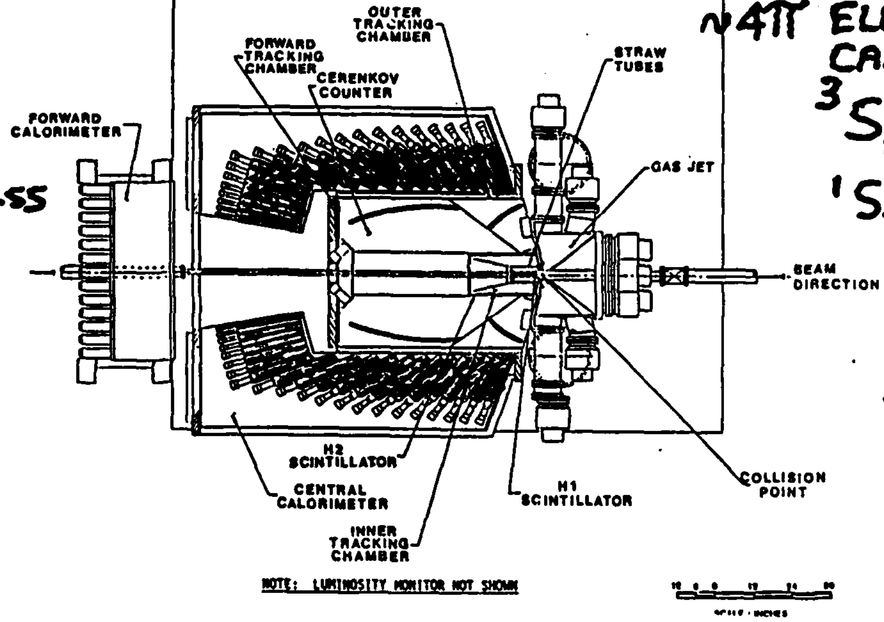
$\bar{p}p \to e^+e^-$



FERMILAB E-760

FERMILAB – FERRARA – GENOA – IRVINE
NORTHWESTERN – PENN STATE – TORINO

■ Pb glass



$\sim 4\pi$ ELECTROMAGNETIC CALORIMETER

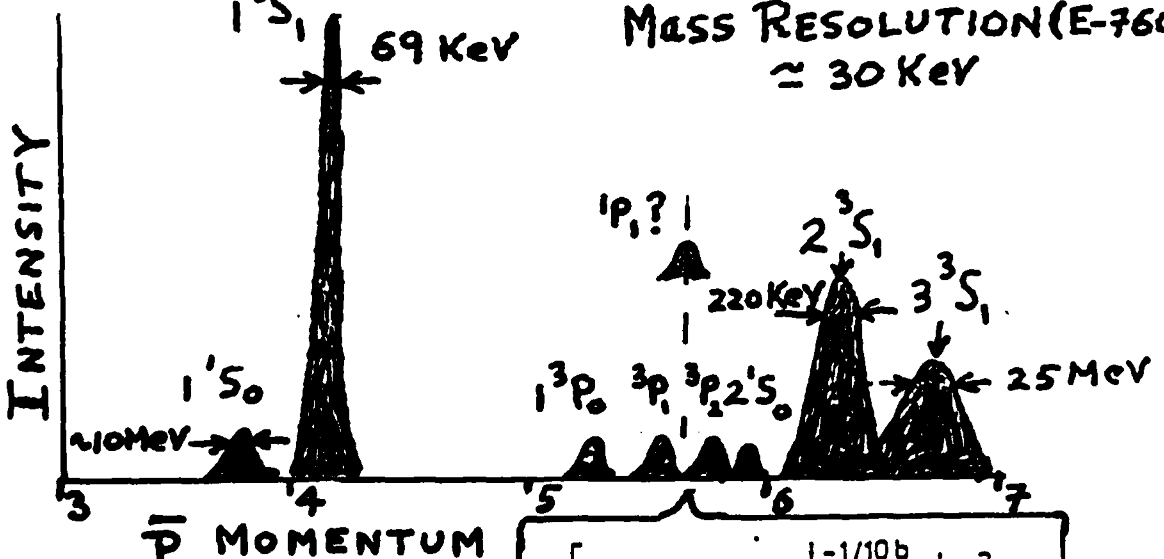
$^3S_1 \to e^+e^-$

$^1S_0 \to \gamma\gamma$

$^3P \to {}^3S_1\gamma$
$\quad \hookrightarrow e^+e^-$

etc.

MASS RESOLUTION (E-760) $\simeq$ 30 KeV



FINE, HYPERFINE STRUCTURE

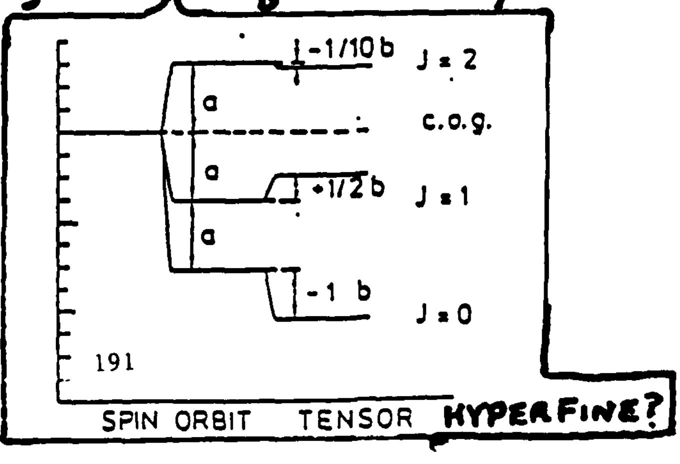
$$\Delta M = a < L \cdot S > + b < T > + c < S_1 \cdot S_2 >$$

OF P-STATES?

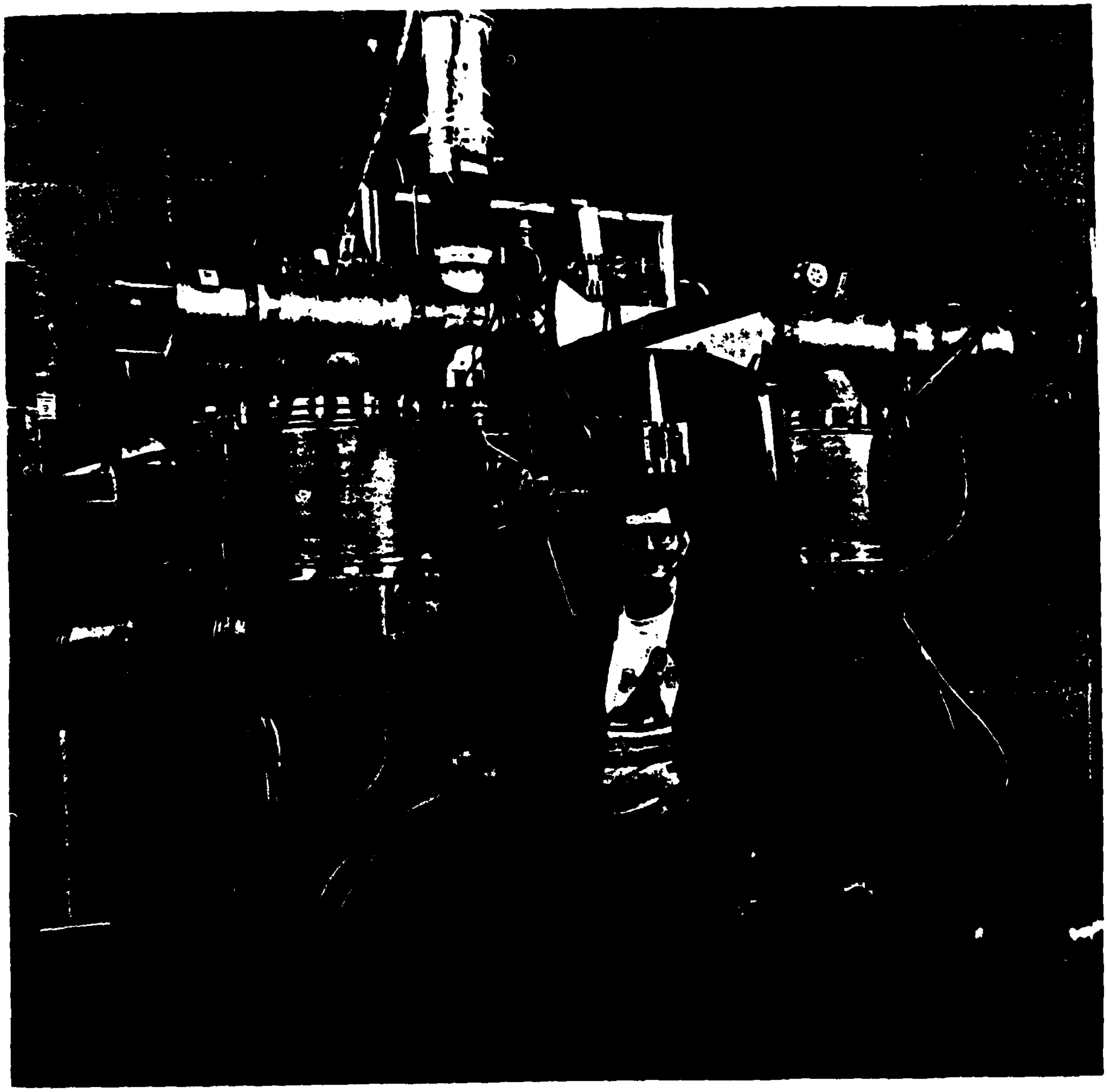
$a \sim 35$ MeV ?

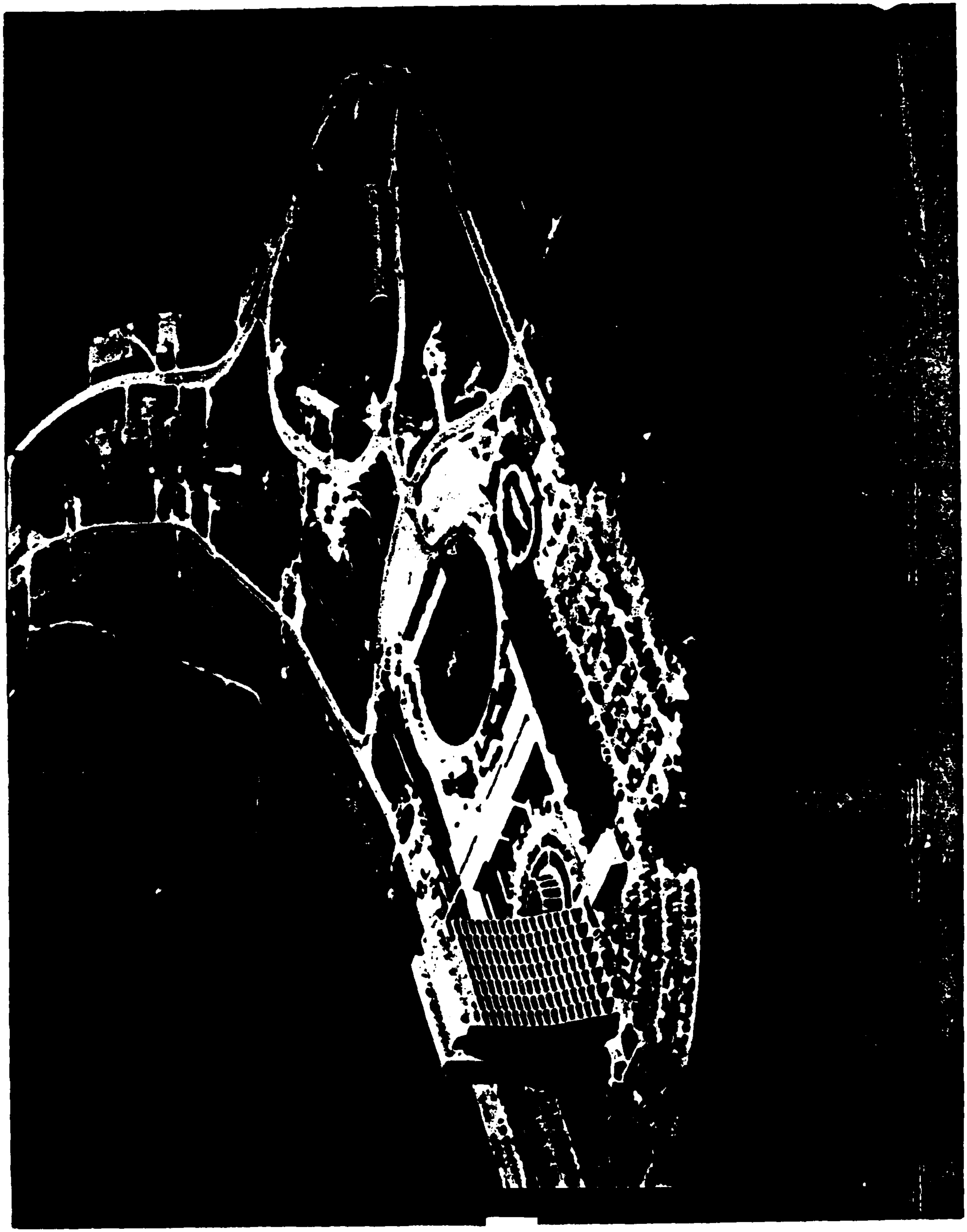
$b \sim 40$ MeV ?

$c = 0$ Confinement in Scalar gluonic field?



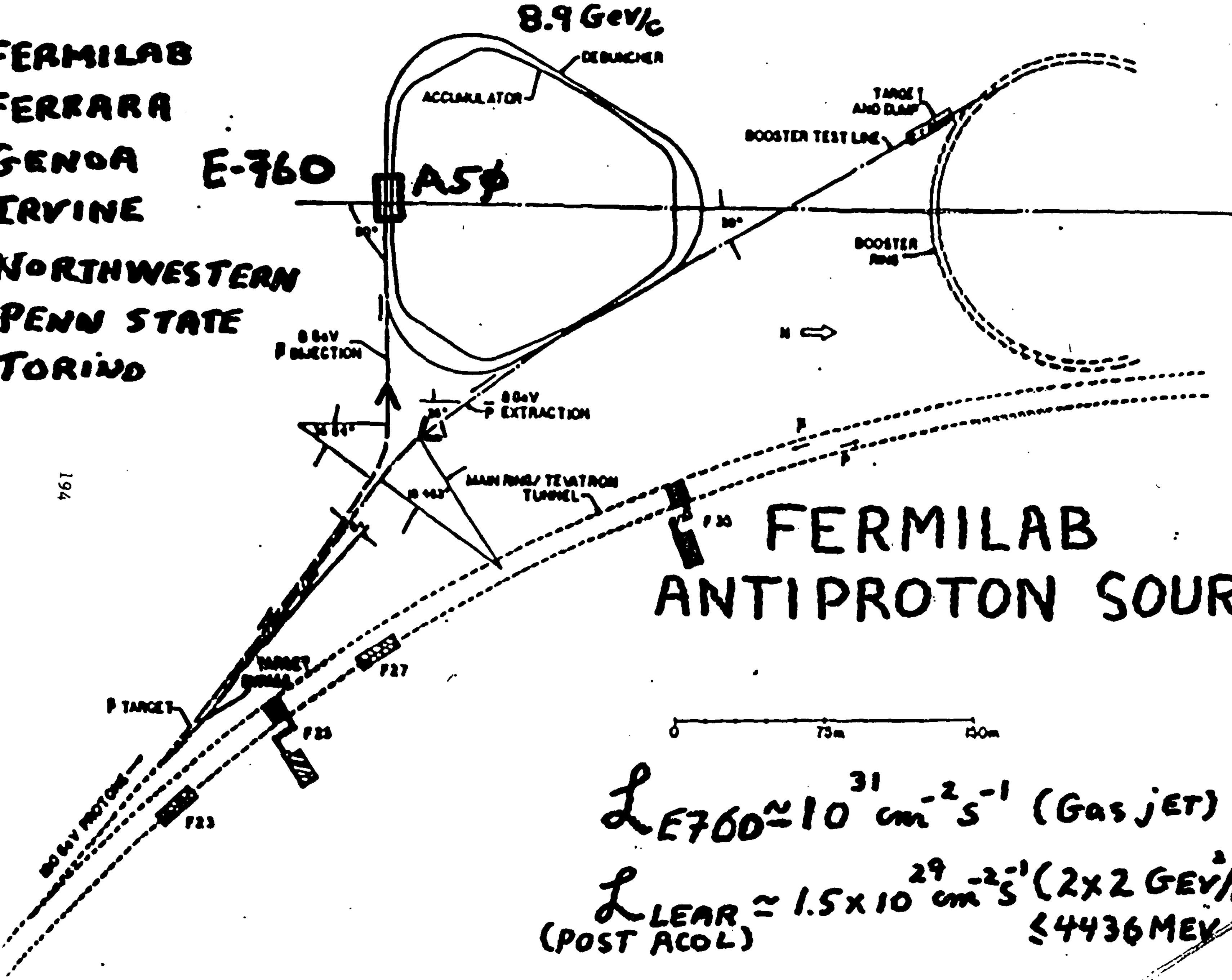
87-603-2 2.8.





FERMILAB
FERRARA
GENOA
IRVINE
NORTHWESTERN
PENN STATE
TORINO

E-760



FERMILAB ANTIPROTON SOURCE

$\mathcal{L}_{E760} \simeq 10^{31}\ cm^{-2} s^{-1}$ (Gas jet)

$\mathcal{L}_{LEAR} \simeq 1.5 \times 10^{29}\ cm^{-2} s^{-1}$ $(2 \times 2\ GeV/c^2)$
(POST ACOL) $\lesssim 4436\ MeV$

LOOKING AT CP INVARIANCE AND QUANTUM MECHANICS IN $J/\psi \to \Lambda\bar{\Lambda}$ DECAY

M.H. TIXIER ET. AL. PHYS. LETT. 212B, 523 (1988)

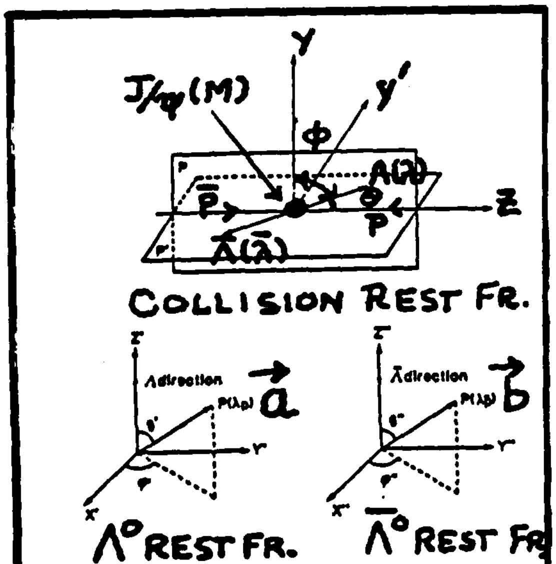


Fig. 1. Λ, $\bar{\Lambda}$, p, $\bar{p}$, π^+ and π^- angles.

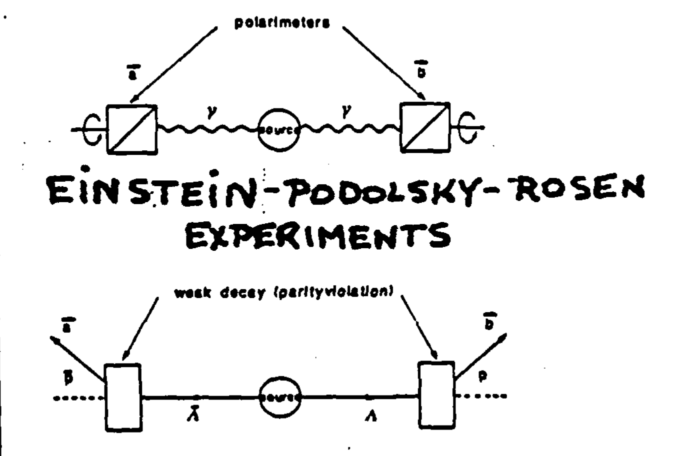


Fig. 2. Analogy between $\Lambda\bar{\Lambda}$ decays and traditional EPR experiments.

N.A. TÖRNQUIST PHYS. LETT. 117B, 1 (1986)

$$\frac{\partial\sigma}{\partial\cos\theta\,\partial\Omega'\,\partial\Omega''}$$

1) CP INVARIANT
2) NO ASSUMPTION ON REL. $\Lambda,\bar{\Lambda}$ POLARIZATION

$$\propto 2\left[1-(P_\Lambda^2/E_\Lambda^2)\sin^2\theta\right](1-\alpha_\Lambda a_n b_n) + (P_\Lambda^2/E_\Lambda^2)\sin^2\theta\left[1-\alpha_\Lambda^2(\vec{a}\cdot\vec{b}-2a_x b_x)\right]$$

a) $P_\Lambda^2/E_\Lambda^2 = 0.48\,(J/\psi)$, $\alpha_\Lambda^2 = 0.412$

b) $\hat{n}$ orthogonal to $\vec{N}_{y'}$ (J/ψ polarization) and $\hat{x}$

1847 $J/\psi \to \Lambda\bar{\Lambda}$ EVENTS
(8.6×10^6 J/ψ DECAYS

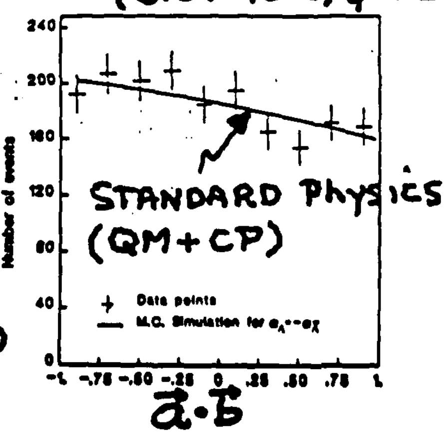


Fig. 7. The $a\cdot b$ distribution. MC simulation and data

TO TEST CP, SET $\alpha_\Lambda^2 = -\alpha_\Lambda\alpha_{\bar{\Lambda}}$. Assuming Validity of Q.M., $\alpha_{\bar{\Lambda}}$ IS EXTRACTED FROM $\vec{a}\cdot\vec{b}$ DISTRIBUTION ⇒
$A = (\alpha + \bar{\alpha})/(\alpha - \bar{\alpha}) = 0.01 \pm 0.10$ (−0.07±0.09, P. BARNES ET. AL. PHYS. ... 1988 ... 117 (1988))

FURTHER TESTS OF CP INVARIANCE IN $J/\psi \to \Lambda^0 \overline{\Lambda^0}$

1) GOAL: 10^{-4} ERROR IN A

2) PRESENT LIMITS: $\sim 10^{-1}$

3) FIRST STEP $\Rightarrow 10^{-2}$

1) J. DONOGHUE ET AL, PR D34, 833 (1986)

2) L. WOLFENSTEIN, ANN. REV. NUCL. PART. SCI 36, 137 (1986)

E-760: $\text{RATE} \simeq (5\times 10^{31}\,\text{cm}^{-2}\,\text{s}^{-1})(10^{-30}\,\text{cm}^{2})\underbrace{(0.13\times 10^{-2})}_{\text{BR } J/\psi \to \Lambda\overline{\Lambda}}$

$$*\underbrace{(0.64)}_{\Lambda \to p\pi^-}\underbrace{(0.64)}_{\overline{\Lambda^0} \to \overline{p}\pi^+} = 0.027\ \text{SEC}^{-1}$$

BR

EXTRAPOLATE DM2 RESULTS (2×10^{3} EVTS.) TO 10^{-2} LEVEL (2×10^{5} EVENTS)

$$\frac{2\times 10^{5}\ \text{EVTS}}{0.027\ \text{SEC}^{-1}} \Rightarrow 7.4\times 10^{6}\ \text{SEC (2.8 months)}$$

WILL PROBABLY GET DONE FOR FREE (SYSTEMATIC ERRORS ??)

4) NEXT STEP $\Rightarrow 10^{-3}$

REQUIRES 2×10^{7} $J/\psi \to \Lambda^0\overline{\Lambda^0}$, OR $\sim 10^{10}$ J/ψ's !!

J/ψ FACTORY @ $\mathcal{L} \simeq 10^{33}\,\text{cm}^{-2}\,\text{SEC}^{-1}$

BEST BET IS PROBABLY e^-e^+ LINEAR COLLIDER?

RARE MODES OF NUCLEON-ANTINUCLEON ANNIHILATION

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10 MAY 1989

RARE MODES OF $N\bar{N}$ ANNIHILATION

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PRODUCTION OF $J^{\pi C}$ EXOTICS IN $\bar{N}N \rightarrow$ mesons

PRODUCTION OF

$J^{\pi C}$ EXOTICS IN $\bar{N}N \rightarrow$ mesons

What is a $J^{\pi C}$ exotic meson?

J = total angular momentum

π = parity ($\pm$)

C = charge conjugation parity ($\pm$)

$\boxed{\text{$J^{\pi C}$ exotic quantum numbers cannot correspond to a quark-antiquark ($Q\bar{Q}$) system}}$

as for ordinary mesons (π, η, ρ, ω ...)

Examples: $J^{\pi C} = 0^{--}, 0^{+-}, 1^{-+}$ are exotic

$\Rightarrow$ must have more complicated structure than $Q\bar{Q}$ $\Rightarrow$ $Q^2\bar{Q}^2$, $Q\bar{Q}g$ ...

excitation of the gluonic field

THEORETICAL PREDICTIONS FOR MASSES OF EXOTICS

consider $Q\bar{Q}g$ "hybrids" $(0^{-+} \text{ or } 1^{--})_{Q\bar{Q}} \otimes \begin{cases} TE\ (1^{+-}) \\ TM\ (1^{--}) \end{cases}$

$\uparrow$ $^1S_0$ $\quad$ $\uparrow$ $^3S_1$

lowest lying are $^3S_1 \otimes TE = \begin{cases} 1^{-+}\ (1^-) & \rho_g \\ 1^{-+}\ (0^+) & \omega_g \end{cases}$

Mass Estimates and Decays:

1) MIT Bag Model (Barnes, Close, deViron, NP B224, 241 (1983)

$M(\rho_g) \approx 1.4\ \text{GeV}$, $M(\omega_g) \approx 1.55\ \text{GeV}$

(Chanowitz, Sharpe NP B222, 211 (1983) give larger M's but $\approx$ same splitting)

2) Flux Tube Model (Isgur, Kokoski, Paton, PRL 54, 869 (1985))

$M(\rho_g) \approx M(\omega_g) \approx 1.9\ \text{GeV}$ [also $0^{+-}(0^-, 1^+), 2^{+-}(0^-, 1^{\ldots}$

Selection Rules: $\rho_g \to \pi^{\pm}B^{\mp}, \pi^0 D$; $\rho_g \not\to \pi\eta, \pi\rho, \rho\omega, K^*\ldots$

3) QCD Sum Rules (Latorre et al, Z. Phys. C34, 347 ('87)

$M(\rho_g) \approx 1.6 - 2.1\ \text{GeV}$

$\rho_g \to \pi\rho, K^*\bar{K}$ large, $\rho_g \to \pi\eta, \pi\eta'$ suppressed

Candidate for a $J^{\pi c}$ exotic resonance:

D. Alde et al, Phys. Lett. B205, 397 (1988)

reaction $\pi^- p \to X^0 n$

$\qquad\qquad \hookrightarrow \pi^0 \eta \; (\ell = 1)$

X^0 seen as interference effect (asymmetry) with $\pi^- p \to A_2^0 n$

$\qquad\qquad \hookrightarrow \pi^0 \eta \; (\ell = 2)$

X^0 is $\boxed{J^{\pi c}(I^G) = 1^{-+}(1^-)}$ exotic

$M = 1406 \pm 20$ MeV, $\Gamma = 180 \pm 30$ MeV

Note: X should be accessible in $\bar{N}N \to \pi X$

$\hookrightarrow$ look for optimum channels

Experimental Searches for Exotics

1) LEAR at CERN

JETSET, CRYSTAL BARREL, OBELIX

2) Brookhaven AGS E818 Chung et al

$\pi^- p \to \rho_g^- p$ at 12 GeV/c

Decay chain: $\rho_g^- \to \pi^- f$, $f \to \delta^+ \pi^-$, $\delta^+ \to K^+ \bar{K}^0$, $\bar{K}^0 \to \pi^+ \pi^-$

overall reaction $\pi^- p \to K^+ \pi^- 3\pi^- p$

3) KEK (Japan)

$\pi^- p \to \rho_g^- p$ at 6 GeV/c

Decay chain: $\rho_g^- \to \pi^- \eta$, $\eta \to 2\gamma$

Production of $J^{\pi C}$ exotics in $\bar{p}p \to \pi^0 X^0$

$J^{\pi C}(I^G)$ of X	$\bar{N}N(L=0) \to \pi^0 X^0(\ell_f)$	$\bar{N}N(L=1) \to \pi^0 X^0(\ell_f)$
$0^{--}(0^-)$	${}^{33}S_1\ (\ell_f=1)$	—
$0^{--}(1^+)$	${}^{13}S_1\ (\ell_f=1)$	—
$0^{--}(0^+,1^-)$	—	—
$0^{+-}(0^-)$	—	${}^{31}P_1\ (\ell_f=1)$
$0^{+-}(1^+)$	—	${}^{11}P_1\ (\ell_f=1)$
$0^{+-}(0^+,1^-)$	—	—
$1^{-+}(0^+)$ ω_g	${}^{31}S_0\ (\ell_f=1)$	${}^{33}P_1\ (\ell_f=0,2),\ {}^{33}P_2\ (\ell_f=2)$
$1^{-+}(1^-)$ ρ_g	${}^{11}S_0\ (\ell_f=1)$	${}^{13}P_1\ (\ell_f=0,2),\ {}^{13}P_2\ (\ell_f=2)$
$1^{-+}(0^-,1^+)$	—	—

C conservation is strong constraint!
see X^0 with both $I=0,1$

Production of $J^{\pi C}$ exotics in $\bar{p}p \to \pi^{\pm} X^{\mp}$

$J^{\pi C}(I^G)$ of X	$\bar{p}p(L=0) \to \pi^{\pm} X^{\mp}(\ell_f)$	$\bar{p}p(L=1) \to \pi^{\pm} X^{\mp}(\ell_f)$
$0^{--}(1^-)$	$^{33}S_1\ (\ell_f=1)$	$^{13}P_0\ (\ell_f=0),\ ^{13}P_2\ (\ell_f=2)$
$0^{--}(1^+)$	$^{13}S_1\ (\ell_f=1)$	$^{33}P_0\ (\ell_f=0),\ ^{33}P_2\ (\ell_f=2)$
$0^{+-}(1^-)$	$^{11}S_0\ (\ell_f=0)$	$^{13}P_1,\ ^{31}P_1\ (\ell_f=1)$
$0^{+-}(1^+)$	$^{31}S_0\ (\ell_f=0)$	$^{33}P_1,\ ^{11}P_1\ (\ell_f=1)$
$1^{-+}(1^-)$	$^{11}S_0(\ell_f=1),\ ^{33}S_1(\ell_f=1)$	$^{13}P_1,\ ^{31}P_1(\ell_f=0,2),\ ^{13}P_2(\ell_f=$
$1^{-+}(1^+)$	$^{31}S_0(\ell_f=1),\ ^{13}S_1(\ell_f=1)$	$^{33}P_1,\ ^{11}P_1(\ell_f=0,2),\ ^{33}P_2(\ell_f=$

no constraint from C
I=0 X forbidden

'roduction of $J^{\pi C}$ exotics in $\bar{p}n \to \pi^- X^0$

$J^{\pi C}(I^G)$ of X	$\bar{p}n(L=0) \to \pi^- X^0$	$\bar{p}n(L=1) \to \pi^- X^0$
$0^{--}(0^-,1^-)$	$^{33}S_1(\ell_f=1)$	—
$0^{--}(0^+,1^+)$	—	$^{33}P_0(\ell_f=0)$, $^{33}P_2(\ell_f=2)$
$0^{+-}(0^-,1^-)$	—	$^{31}P_1(\ell_f=1)$
$0^{+-}(0^+,1^+)$	$^{31}S_0(\ell_f=0)$	$^{33}P_1(\ell_f=1)$
$1^{-+}(0^-,1^-)$	$^{33}S_1(\ell_f=1)$	$^{31}P_1(\ell_f=0,2)$
$1^{-+}(0^+,1^+)$	$^{31}S_0(\ell_f=1)$	$^{33}P_1(\ell_f=0,2)$, $^{33}P_2(\ell_f=2)$

no constraint from C
see both $I=0,1$

NON-STRANGE DECAY MODES OF J=0,1 EXOTICS

consider PS+PS, PS+V, PS+T, VV, PS+S

"η" = $\{\eta, \eta'\}$, "ω" = $\{\omega, \varphi\}$, "f" = $\{f, f'\}$, "σ" = $\{\sigma, S^*\}$, "D" = $\{D, E\}$

$J^{\pi c}(I^G)$	Allowed Decays $X^0 \to M_1 M_2 (\ell)$
$0^{--}(0^-)$	$\pi^0\rho^0, \pi^\pm\rho^\mp, \eta\omega\ (\ell=1)$
$0^{--}(0^+)$	$\pi^\pm A_2^\mp (\ell=2), \pi^\pm\delta^\mp (\ell=0)$
$0^{--}(1^-)$	$\pi^\pm\rho^\mp (\ell=1)$
$0^{--}(1^+)$	$\pi^0\omega, \eta\rho^0 (\ell=1), \pi^\pm A_2^\mp (\ell=2), \pi^\pm\delta^\mp (\ell=0)$
$0^{+-}(0^-)$	$\pi^0 B^0, \pi^\pm B^\mp (\ell=1)$
$0^{+-}(0^+)$	$\pi^+\pi^- (\ell=0), \rho^+\rho^- (\ell=0,2), \pi^\pm A_1^\mp (\ell=1)$
$0^{+-}(1^-)$	$\pi^\pm B^\mp (\ell=1)$
$0^{+-}(1^+)$	$\pi^+\pi^- (\ell=0), \rho^+\rho^- (\ell=0,2), \pi^\pm A_1^\mp (\ell=1), \pi^0 H (\ell=1)$
$1^{-+}(0^-)$	$\pi^\pm\rho^\mp (\ell=1), \pi^\pm B^\mp (\ell=0,2)$
$1^{-+}(0^+)$ ω_g	$\pi^0\pi^0, \pi^+\pi^- (\ell=1), \eta\eta (\ell=1), \rho^0\rho^0, \rho^+\rho^- (\ell=1,3)$ $\omega\omega (\ell=1,3), \pi^0 A_1^0, \pi^\pm A_1^\mp (\ell=0,2), \pi^0 A_2^0, \pi^\pm A_2^\mp (\ell=2)$
$1^{-+}(1^-)$ ρ_g	$\pi^0\eta (\ell=1), \pi^\pm\rho^\mp (\ell=1), \rho^0\omega (\ell=1,3), \pi^0 D (\ell=0,2)$ $\pi^0 f (\ell=2), \pi^\pm B^\mp (\ell=0,2)$
$1^{-+}(1^+)$	$\pi^+\pi^- (\ell=1), \rho^+\rho^- (\ell=1,3), \pi^\pm A_1^\mp (\ell=0,2)$ $\pi^\pm A_2^\mp (\ell=2)$

Search for $1^{-+}(1^-)$ exotic in $\bar{p}p \to \pi^0\pi^0\eta$

SIGNAL: $\bar{p}p\,({}^1S_0) \to \pi^0 X^0 \; (\ell_f = 1)$
$\quad\quad X^0 \to \pi^0\eta \; (\ell = 1)$

BACKGROUND: $\bar{p}p\,({}^1S_0) \to \pi^0 A_2^0 \; (\ell_f = 2)$
$\quad\quad A_2^0 \to \pi^0\eta \; (\ell = 2)$

$\bar{p}p\,({}^1S_0) \to \pi^0 \delta^0 \; (\ell_f = 0)$
$\quad\quad \delta^0 \to \pi^0\eta \; (\ell = 0)$

also $\sigma\eta\,(\ell_f = 0)$, $f\eta\,(\ell_f = 2)$ couple to $\pi^0\pi^0\eta$

Experimentally, look for $\pi^0\pi^0\eta \to \underline{6\gamma}$ (CRYSTAL BARREL)

Exotics in $\bar{p}p$ Annihilation:

A) All neutral modes

1) $\bar{p}p \to \pi^0 \omega_g \to 2\pi^0 (\ell_f = 1)$ $\quad$ $\pi^0 f$, $\pi^0 \sigma$ backgr.

2) $\bar{p}p \to \pi^0 \omega_g \to \eta\eta \; (\ell_f = 1)$

3) $\bar{p}p \to \pi^0 \rho_g^0 \to \pi^0 \eta \; (\ell_f = 1)$

4) $\bar{p}p \to \pi^0 \rho_g^0 \to \pi^0 f \; (\ell_f = 2)$, $f \to 2\pi^0$

B) Charged Modes:

1) $\bar{p}p \to \pi^\pm \rho_g^\mp \to \pi^\mp B^0 \to \pi^0 \omega \to \pi^0 \gamma$ $\quad$ CRYSTAL BARREL

2) $\bar{p}p \to \pi^\pm \rho_g^\mp \to \pi^\mp D^0 \to \pi^0 \pi^0 \eta$

3) $\bar{p}p \to \pi^\pm \rho_g^\mp \to \pi^\mp \rho^0 \to \pi^+ \pi^-$

Outlook: $\boxed{\text{N}\bar{\text{N}} \text{ annihilation very promising as a means of producing exotic mesons X in reactions } N\bar{N} \to \pi X}$

Difficulties:

1) Γ_X large $\rightsquigarrow$ new states are broad resonance
$\rightsquigarrow$ detailed amplitude analysis need to extract interference effects

2) branching ratios for $N\bar{N} \to \pi X$ likely to be smal
$\rightsquigarrow$ no good theoretical estimate

Advantages:

1) $N\bar{N}$ annihilation potentially rich in gluonic excitations

2) $N\bar{N}$ at rest provides control of initial quantum numbers ($L=0$ or $L=1$)

3) $\bar{p}p \to \pi^0 X^0, \pi^\pm X^\mp$; $\bar{p}n \to \pi^- X^0$ gives quantum number filtration

ANTIPROTON PRODUCTION CALCULATION BY THE MULTISTRING MODEL "VENUS" COMPUTER CODE

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HELD AT BROOKHAVEN NATIONAL LABORATORY
10 MAY 1989

ANTIPROTON PRODUCTION CALCULATION BY MULTISTRING MODEL VENUS COMPUTOR CODE

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WORKSHOP ANTIPROTON TECHNOLOGY
MAY 10,1989

Brookhaven National Laboratory
Upton,New York,11973

Fermi Lab Source Performance

F.E. Mills. N I M P A 271 (1988) 176

Proton Energy E_{lab} = 120 GeV

Antiproton Energy = 8 GeV

Target : Cu

Cross Section Missing Factor $\approx$ 2.5

McGormley.

2 3

Antiproton Source (CERN, Fermi Lab)

Hojvat and Van Ginneken

Empirical formula

$$\frac{E}{\sigma_{ab}} \frac{d^3\sigma}{dp^3} = \left[k(1-x_R)^m \exp(-3p_T^2) \right]$$

$$\times \left[1 + 24 S^{-2} \exp(8 x_R) \right] \left[a \exp(b p_T^2) \exp(-c x_R) \right]$$

$x_R = E/E_{max}$.

$k = 0.065$, $m = 8.0$

Target	a	b	c
H	1.00	0.0	0.0
W	1.69	1.38	1.79
Pb	1.73	1.37	1.83

VENUS

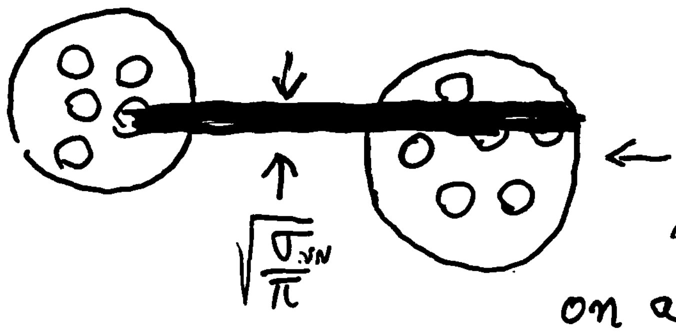
A multistring model for ultrarelativistic heavy ion collision

- model for 'ordinary' collisions (no plasma)
- pp extrapolation (test : pA)
- string fragmentation consistent with e^+e^-, νp, $\bar{\nu} p$, μp data
- Monte Carlo formulation (event generator)
- motivated by Regge theory (like DPM)

Step Structure

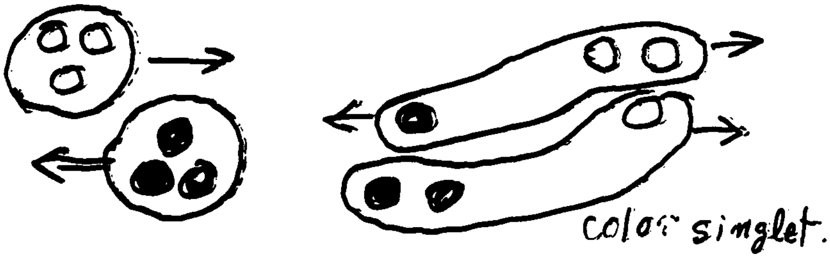
I) Multiple Scattering

Geometry + σ_{NN} determine NN coll



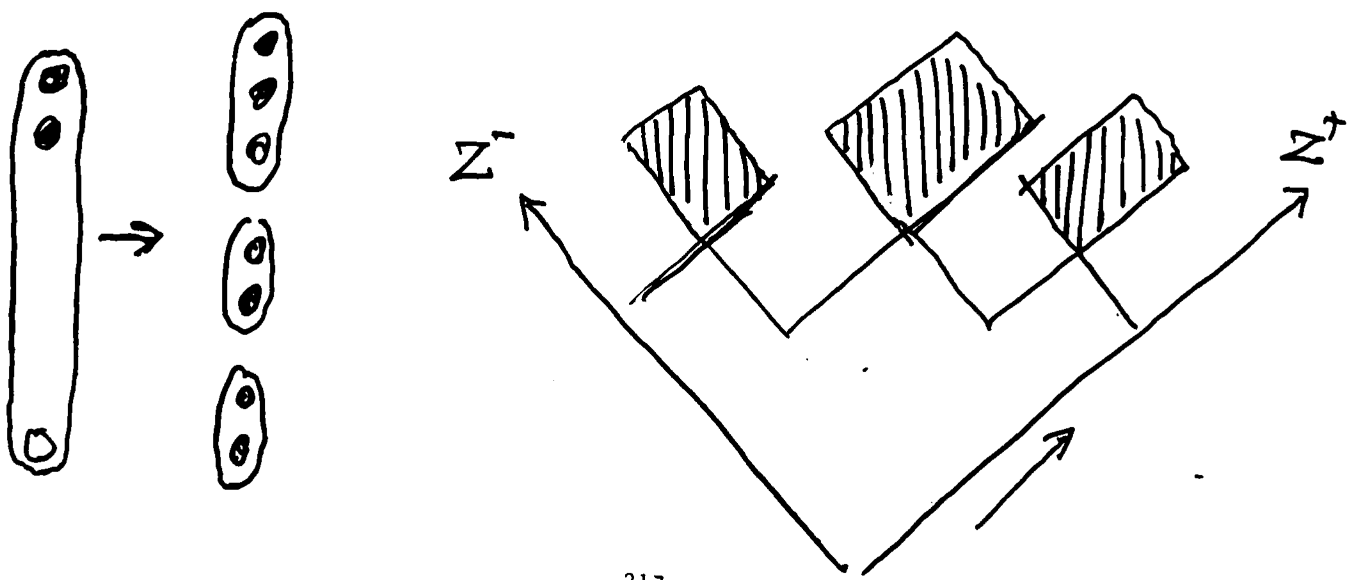
nucleon move on a straight line

II) individual N N collision



$\boxed{\text{color exchange}}$

III) String fragmentation



Multi String Model. Venus Code

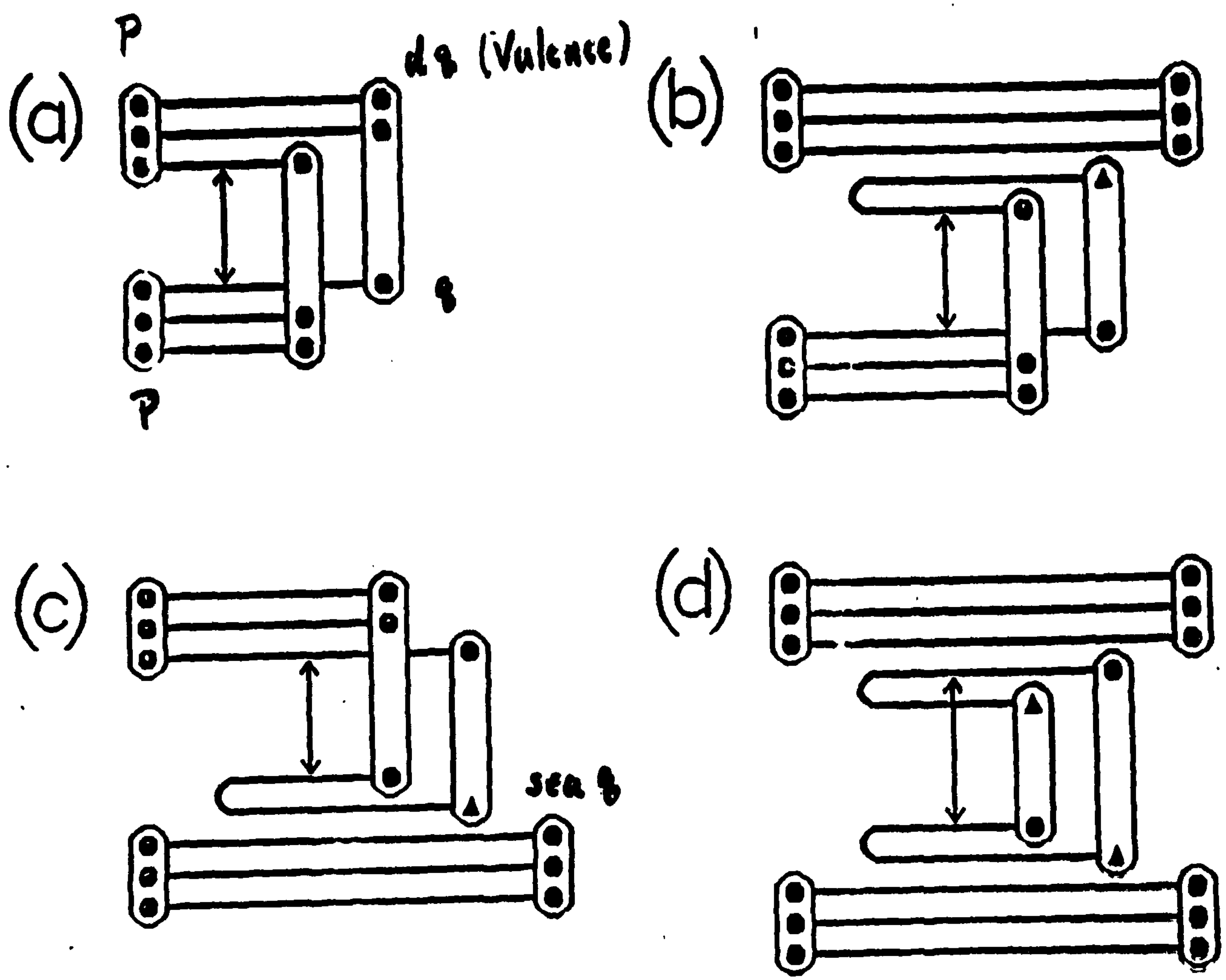
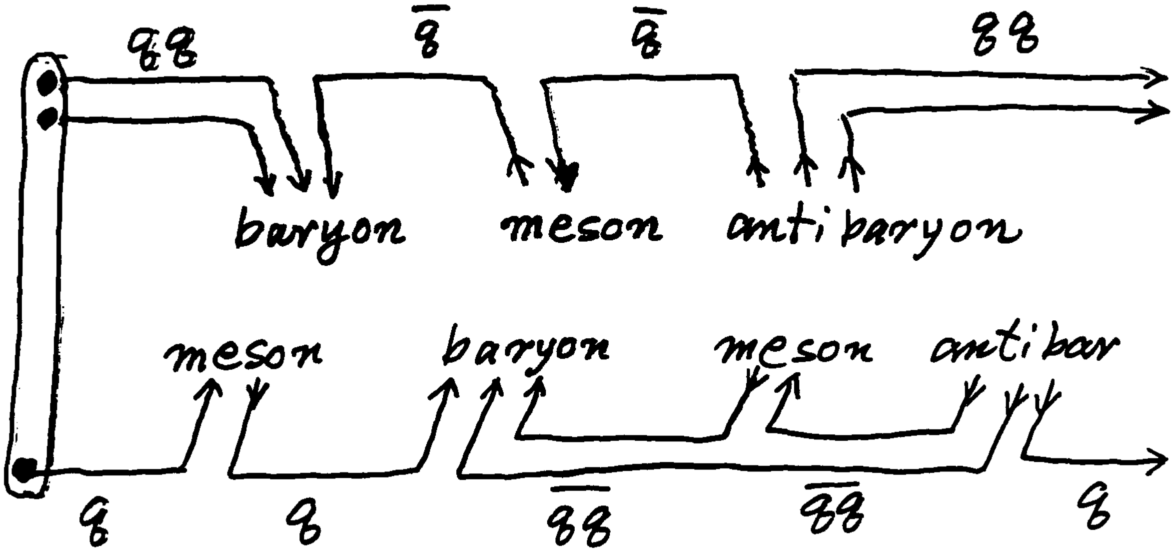
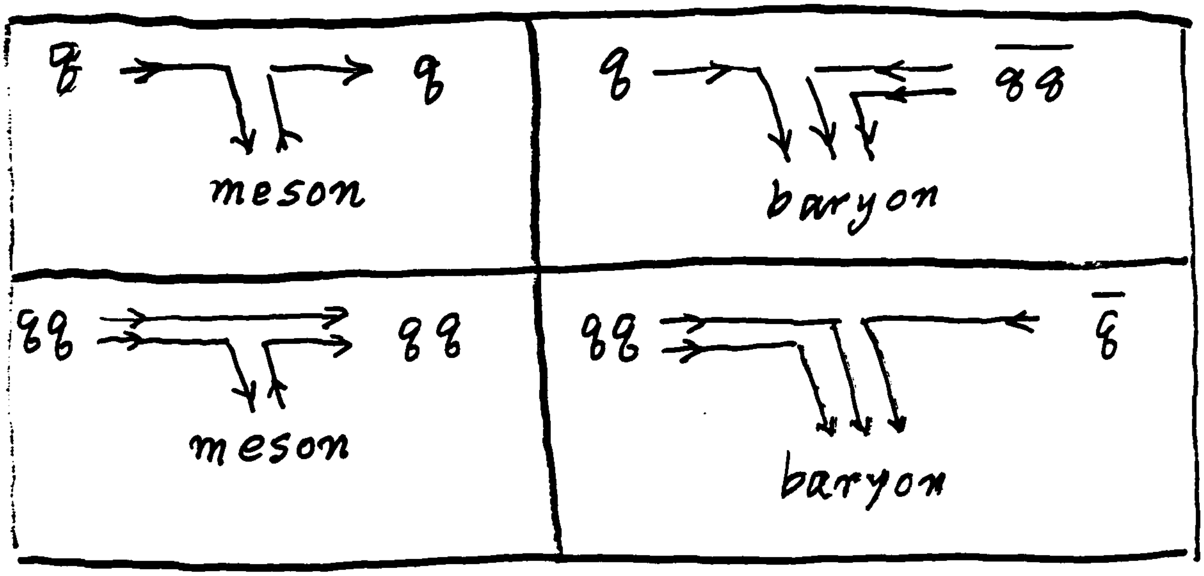


Figure 1

Feynman Field fragmentation



elementary vertices ;



Splitting function (using quark counting)

$$\boxed{f(x) \sim x^{\alpha}(1-x)^{2n-1}}$$

n: number of spectator

$$\alpha = \begin{cases} 3/2 & \text{for baryon prod} \\ 0 & \text{for meson prod} \end{cases}$$

Table 4.1 The Particle Yield For Proton-Proton Collision (%)

Number of Hits:	15000	15000
Lab Energy of Projectile (GeV.)	200	1000
$\bar{p}$	4.53 (5.4)*	11.5 (16.2)*
$\bar{n}$	4.39	11.2
p	128.7	132.3
n	62.3	67.7
$\pi-$	262.4	399.2
$\pi+$	325.1	461.7
γ	735.8	1052.5
k-	15.1	28.4
k+	24.4	41.4
$\Sigma+$	4.39	6.08
$\bar{\Sigma}-$	0.37	1.36
$\Lambda-$	2.0	6.3
$\Lambda+$	14.1	22.3
e-	4.4	6.0
e+	4.4	6.0

* ( ) is calculated by Hojovat and Van Ginneken's empirical formula.

Table 4.2 The Particle Yield For Proton-Pb Collision (%)

Number of Hits:	5822	5773
Lab Energy of Proton (GeV.)	200	1000
$\bar{p}$	7.07(9.0)*	21.38 (29.0)*
$\bar{n}$	6.93	22.37
p	213.59	227.94
n	218.83	226.64
$\pi-$	751.96	1154.70
$\pi+$	765.16	1168.16
γ	1998.35	2921.7
$\kappa-$	27.75	65.70
$\kappa+$	49.51	89.51
$\Sigma+$	28.37	45.27
$\bar{\Sigma}-$	3.48	9.41
$\Sigma-$	6.10	9.41
$\bar{\Sigma}+$	0.66	2.66
$\Lambda-$	0.64	3.02
$\Lambda+$	5.54	9.39
e-	11.33	16.45
e+	11.33	16.45

* ( ) is calculated by Hojovat & Van Ginneken's empirical formula.

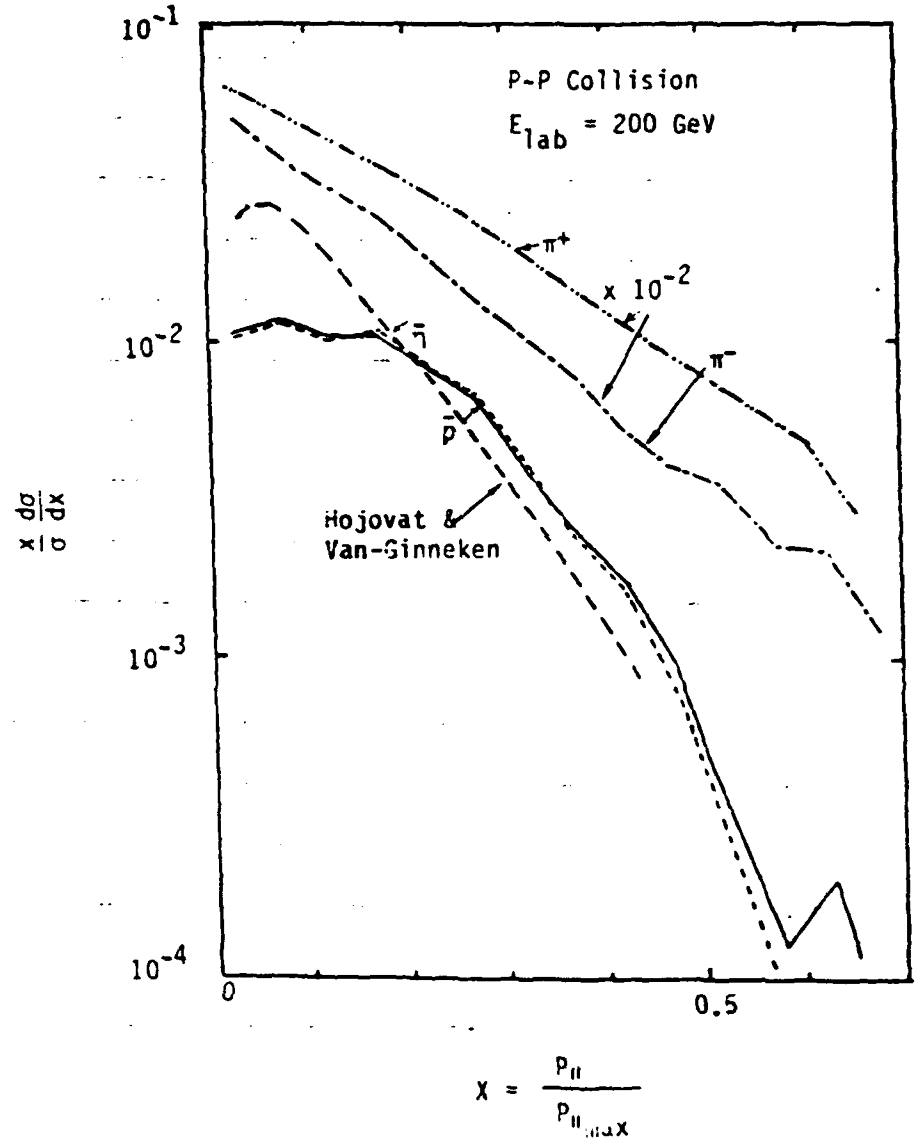

P-P Collision
E lab = 200 GeV
π+
x 10-2
π-
η̄
p̄
Hojovat &
Van-Ginneken
x dσ/σ dx
0
0.5
X = P∥ / P∥max

Figure 3.1

10

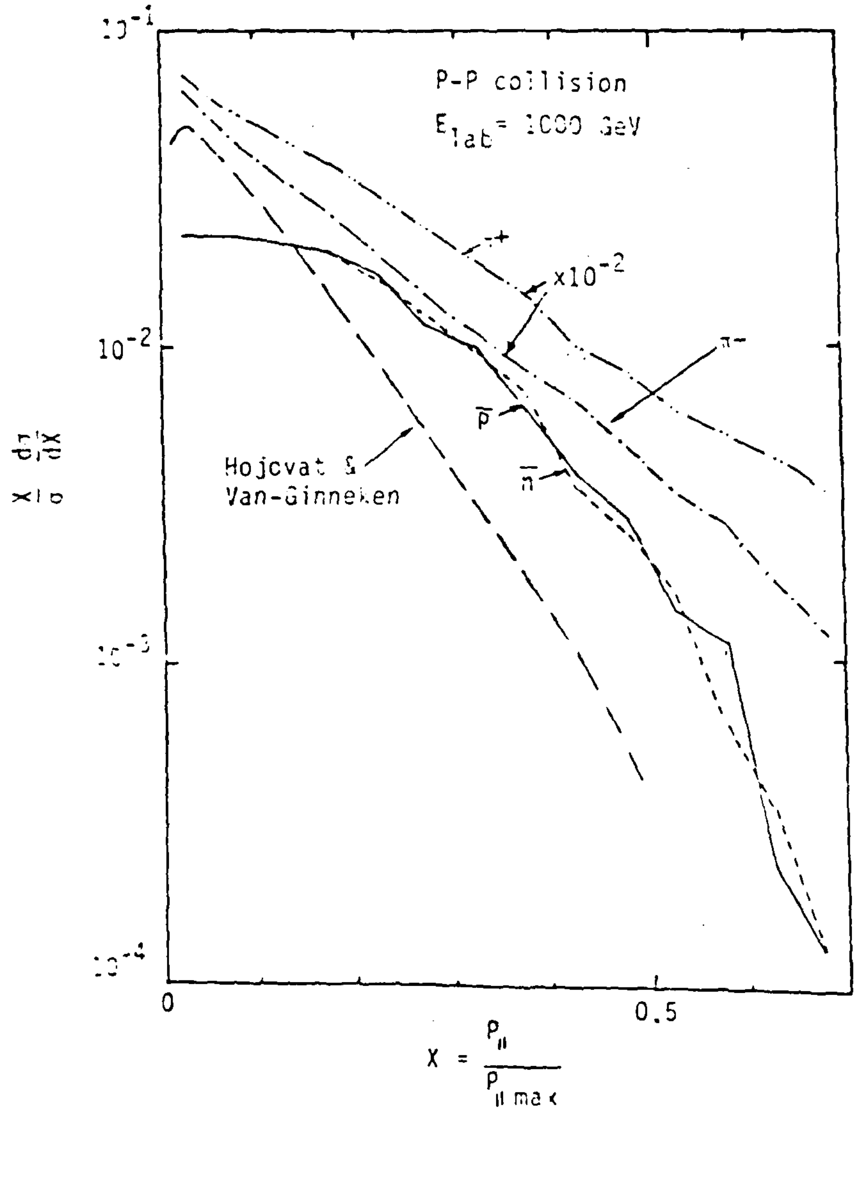
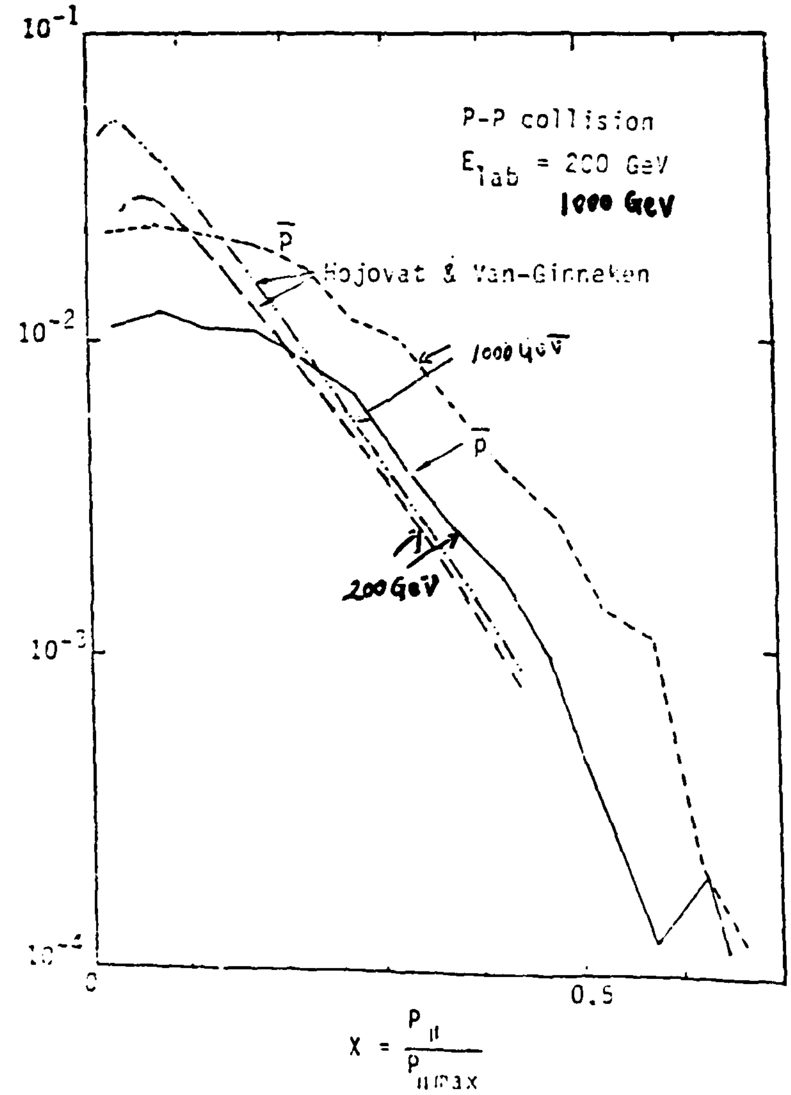

P-P collision
E lab = 1000 GeV
x10^-2
Hojovat &
Van-Ginneken
10^-1
10^-2
10^-3
10^-4
0
0.5
X = P∥ / P∥max

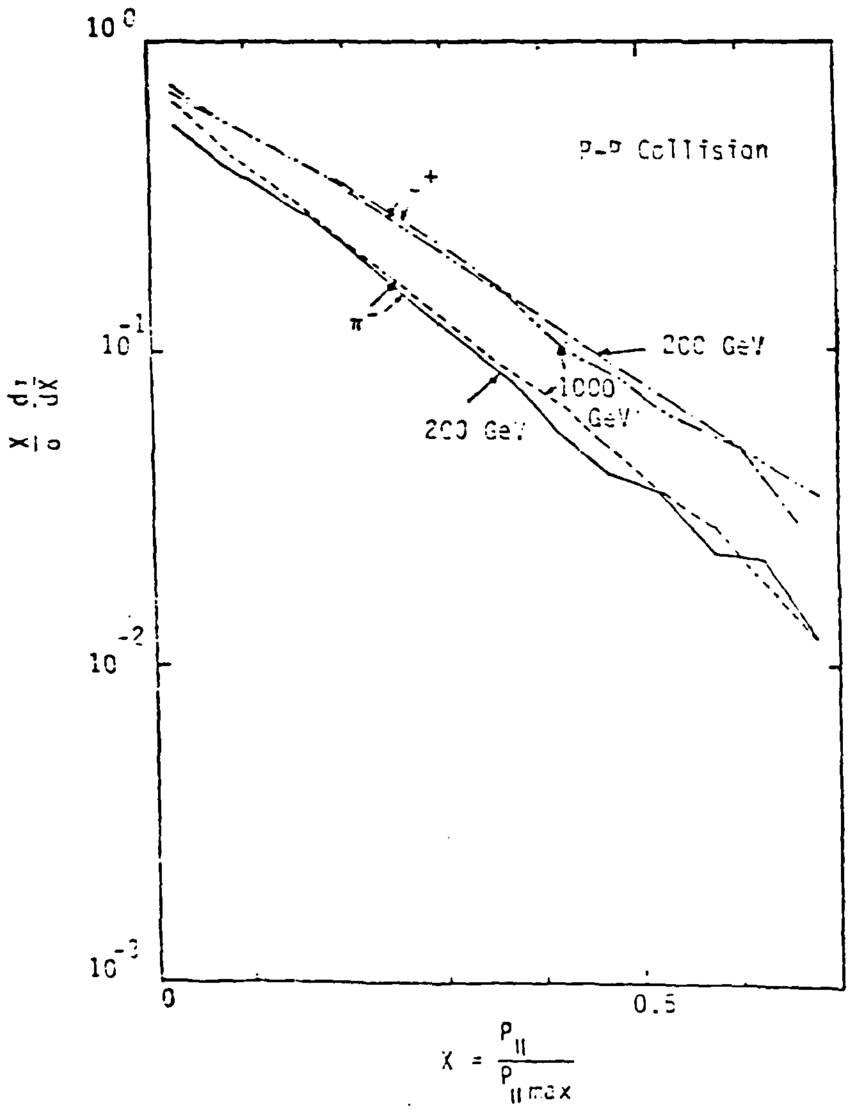
Figure 3.2



Iso. Kinoshita.
quark Cascade Recombination Model
Analytic

Figure 3.3

12



P-P Collision
200 GeV
1000 GeV
200 GeV
π^-
10^0
10^{-1}
10^{-2}
10^{-3}
0
0.5
$X = \frac{P_{\parallel}}{P_{\parallel max}}$
$\frac{X}{\sigma}\frac{d\sigma}{dX}$

Figure 3.4

13

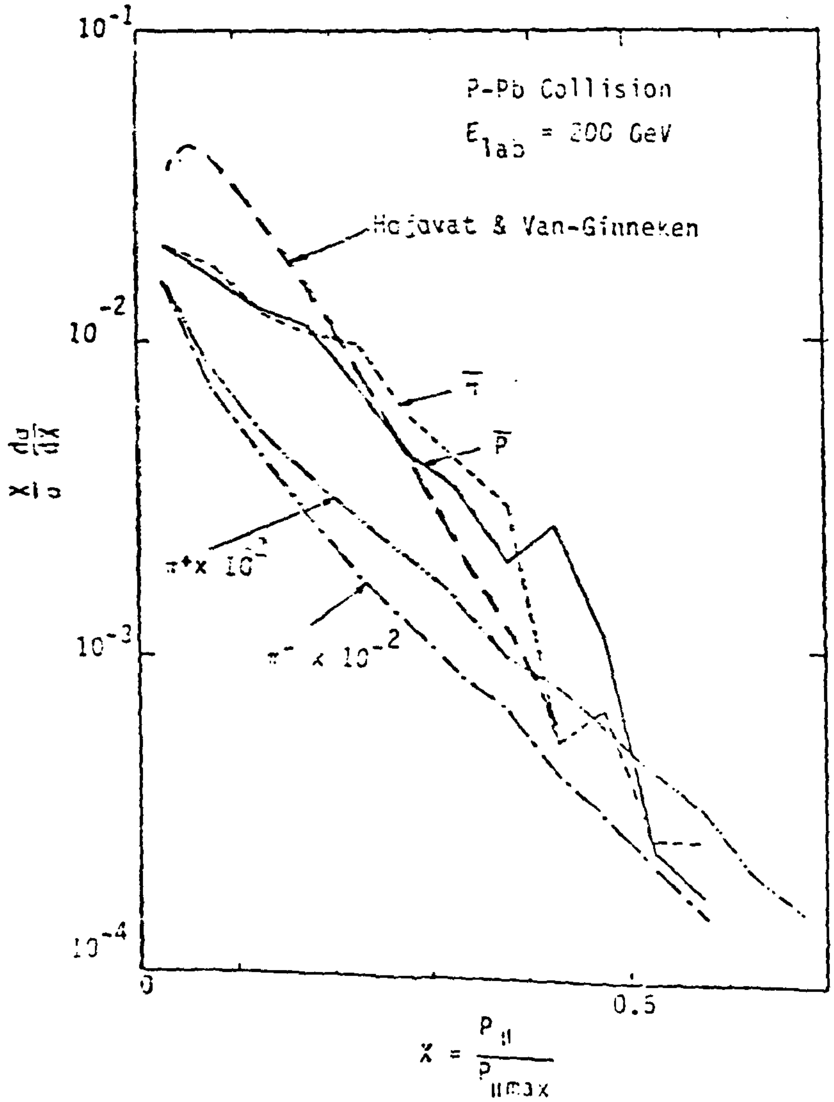
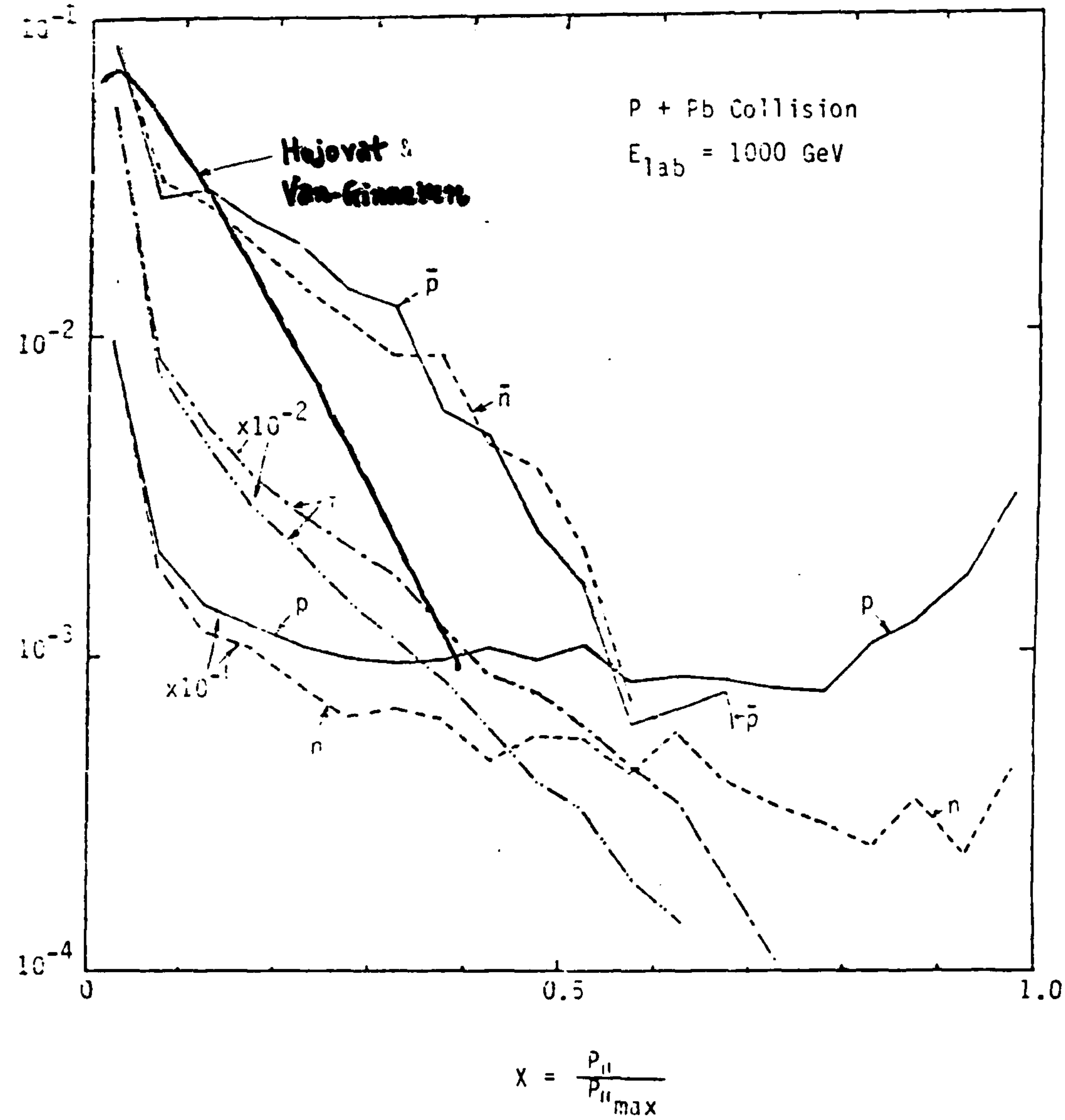

P-Pb Collision
E_lab = 200 GeV
Hojovat & Van-Ginneken
π̄
P̄
π⁺x 10⁻²
π⁻ x 10⁻²
10⁻¹
10⁻²
10⁻³
10⁻⁴
x/σ dσ/dx
0
0.5
X = P∥ / P∥max

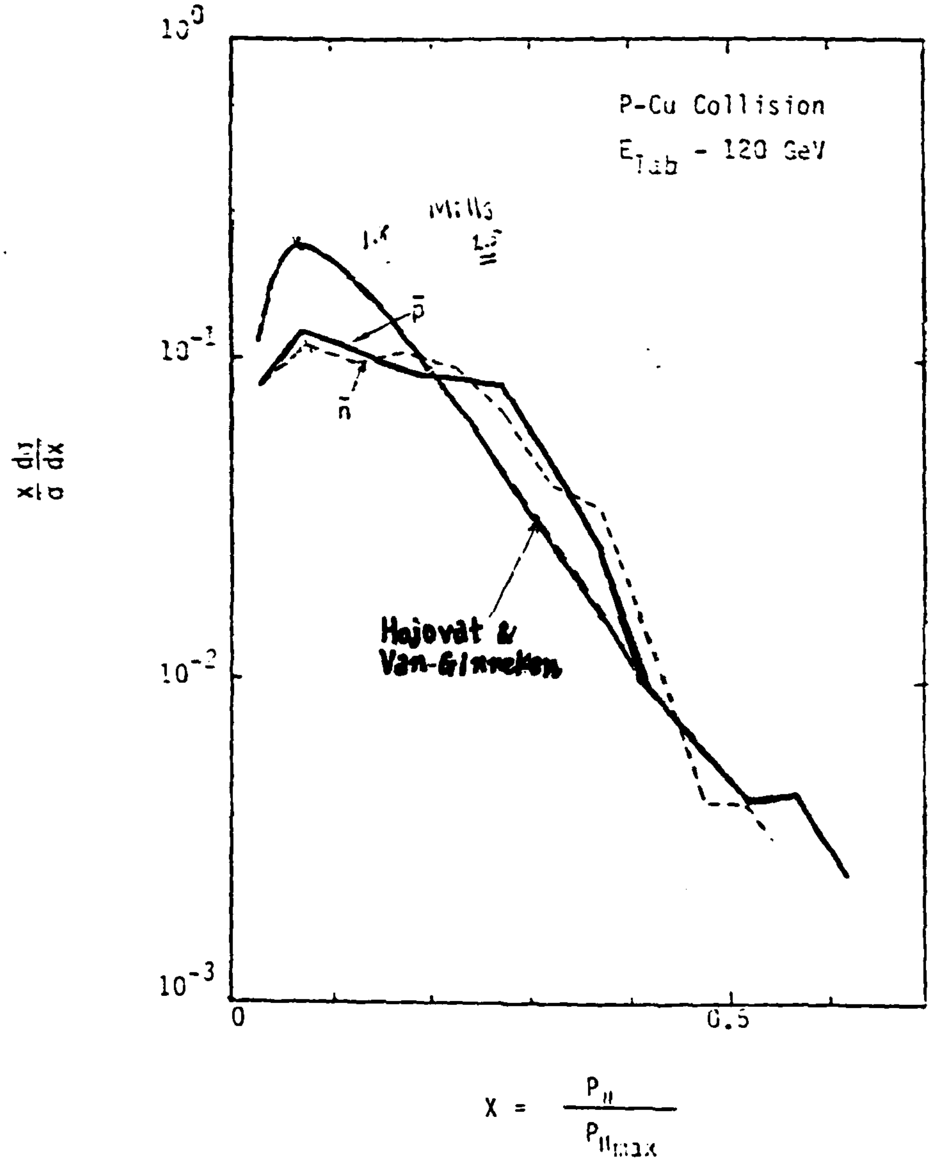
Figure 3.5



P + Pb Collision
E_{lab} = 1000 GeV
Hojovat & Van-Ginneken
$\bar{p}$
$\bar{n}$
x10^{-2}
p
x10^{-1}
n
$\bar{p}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.5
1.0
$X = \frac{P_{\parallel}}{P_{\parallel max}}$

Figure 3.6

16



P-Cu Collision
E_{lab} - 120 GeV
Mills
$\bar{p}$
$\bar{n}$
Hajovat &
Van-Ginneken
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
0.5
$\frac{x}{\sigma}\frac{d\sigma}{dx}$
$X = \frac{P_{\parallel}}{P_{\parallel max}}$

Figure 3.9

Table 4.3 The Particle Yield For Si-Si (%)

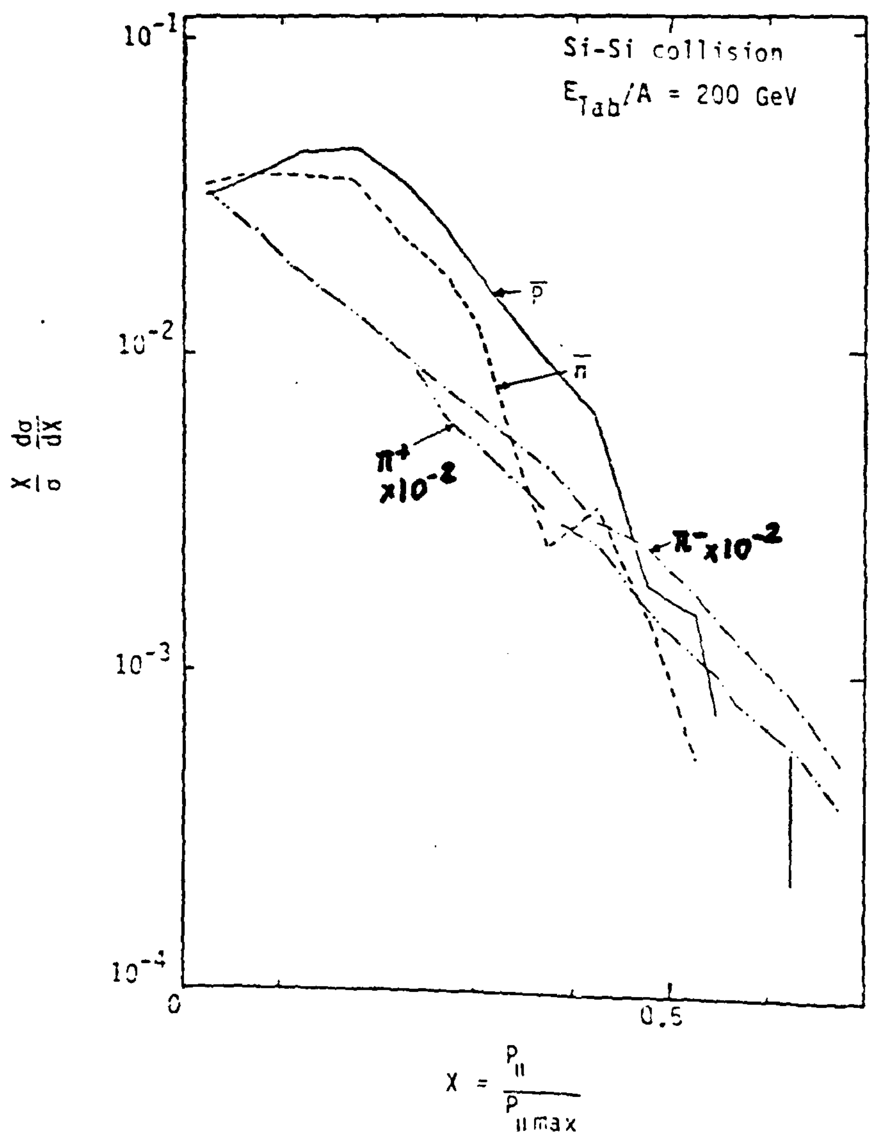
Number of Hits:	9831	9858
Lab Energy of Projectile (GeV./A)	200	1000
$\bar{p}$	26.88 (82.5)*	79.86 (260.5)*
$\bar{n}$	27.41 (81.7)	79.20 (258.4)
p	680.24	710.38 (2238.7)
n	684.46	706.08 (2229.6)
$\pi-$	2931.60	4353.5 (15226.2)
$\pi+$	2935.06	4358.07 (15200.8)

* ( )s are at central collision (b=0)

Table 4.4 The Particle Yield For O-Pb Collision (%)

Number of Hits: Lab Energy of Projectile (GeV./A)	7000 200	876 1000
$\bar{p}$	40.04 (78.6)*	124.77
$\bar{n}$	37.84 (77.8)	122.14
p	153.5 (316.3)	1181.73
n	1235.35 (348.1)	1234.24
$\pi-$	5298.5 (15216.2)	7899.2
$\pi+$	5421.3 (14835.1)	7756.39

* ( )s are at central collision (b=0).



Si-Si collision
E_{lab}/A = 200 GeV
$\bar{p}$
$\bar{n}$
$\pi^{+} \times 10^{-2}$
$\pi^{-} \times 10^{-2}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.5
$\frac{x}{\sigma}\frac{d\sigma}{dx}$
$x = \frac{P_{\parallel}}{P_{\parallel max}}$

Figure 4.1

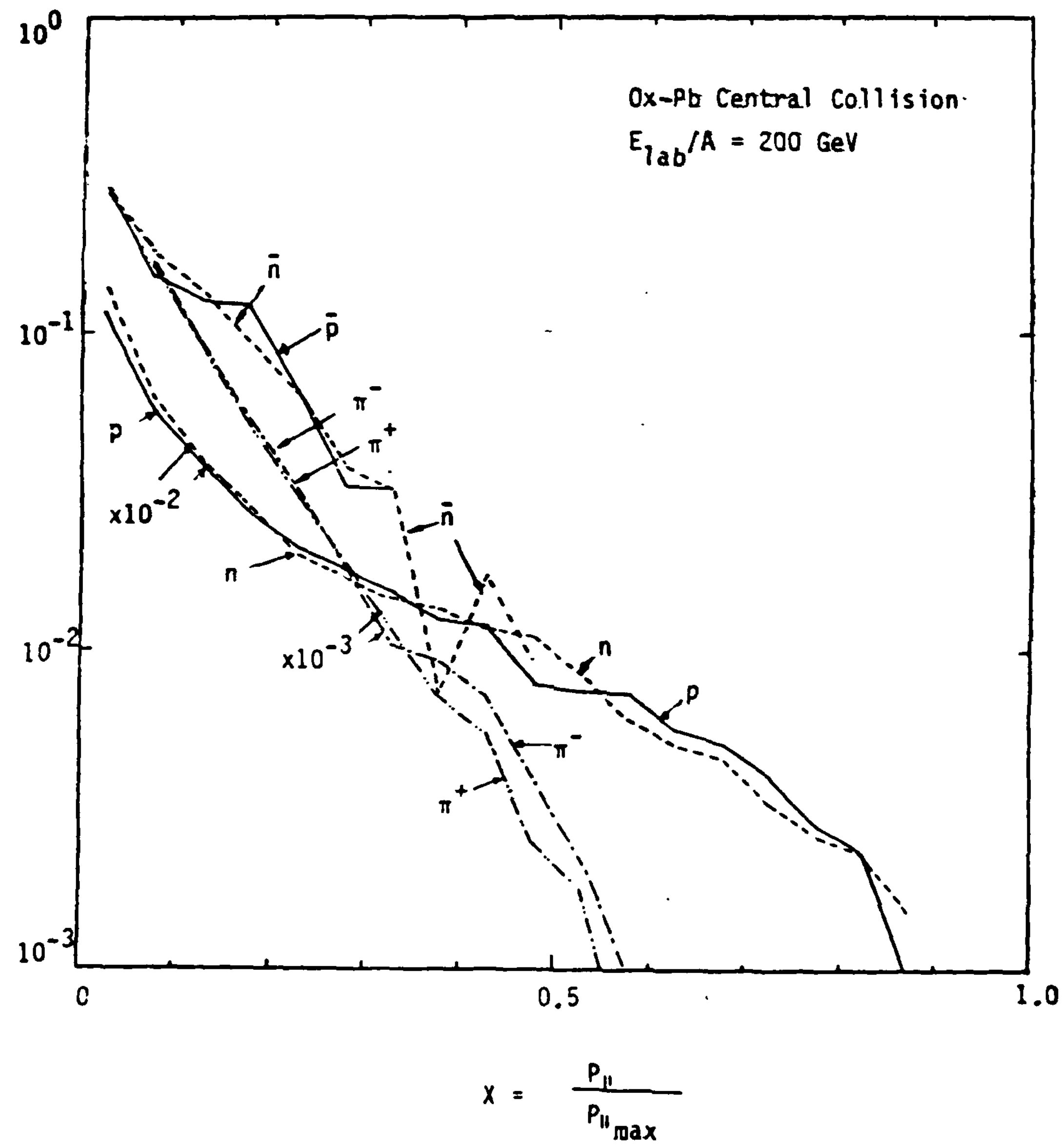
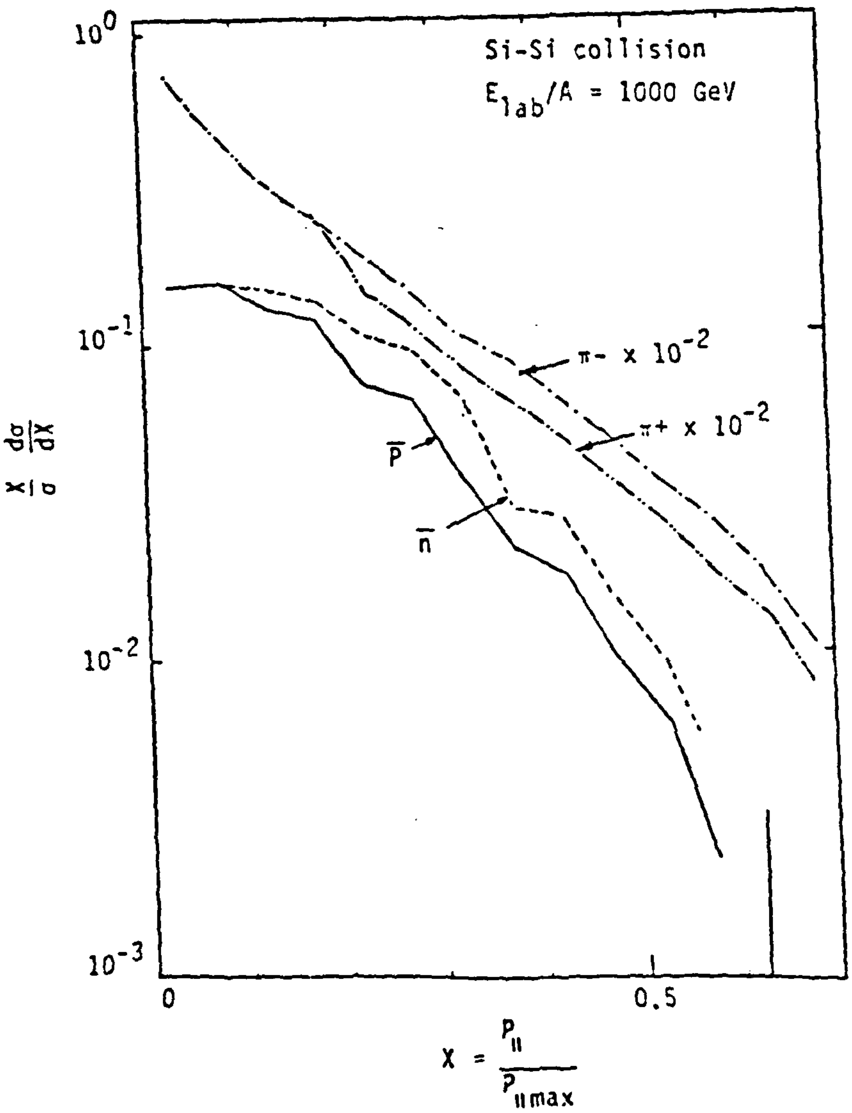
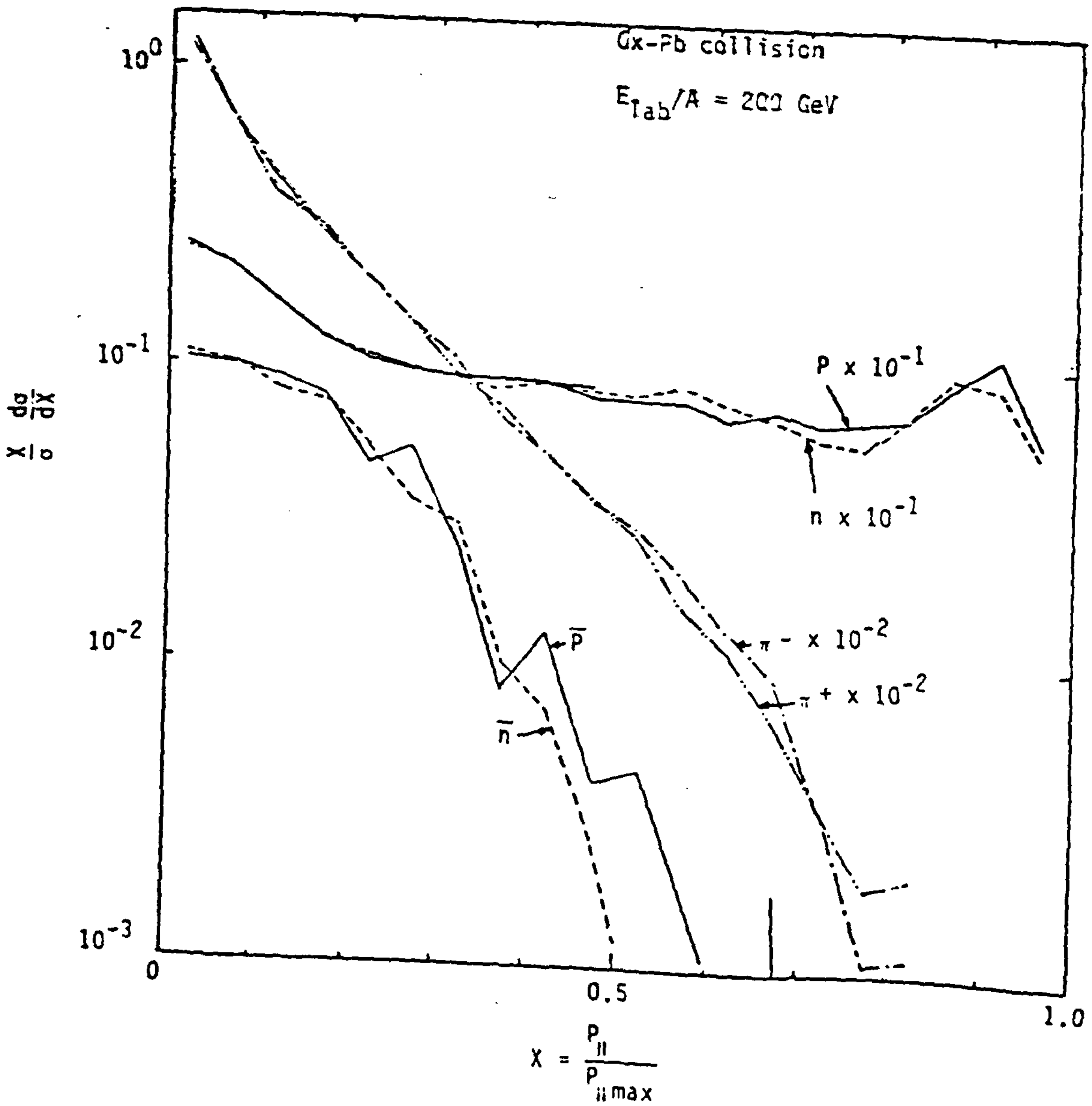

Ox-Pb Central Collision
E lab/A = 200 GeV
10^0
10^{-1}
10^{-2}
10^{-3}
0
0.5
1.0
$\bar{n}$
$\bar{p}$
π^-
π^+
p
x10^{-2}
n
x10^{-3}
$\bar{n}$
n
p
π^-
π^+
$X = \frac{P_{\parallel}}{P_{\parallel max}}$

Figure 4.6



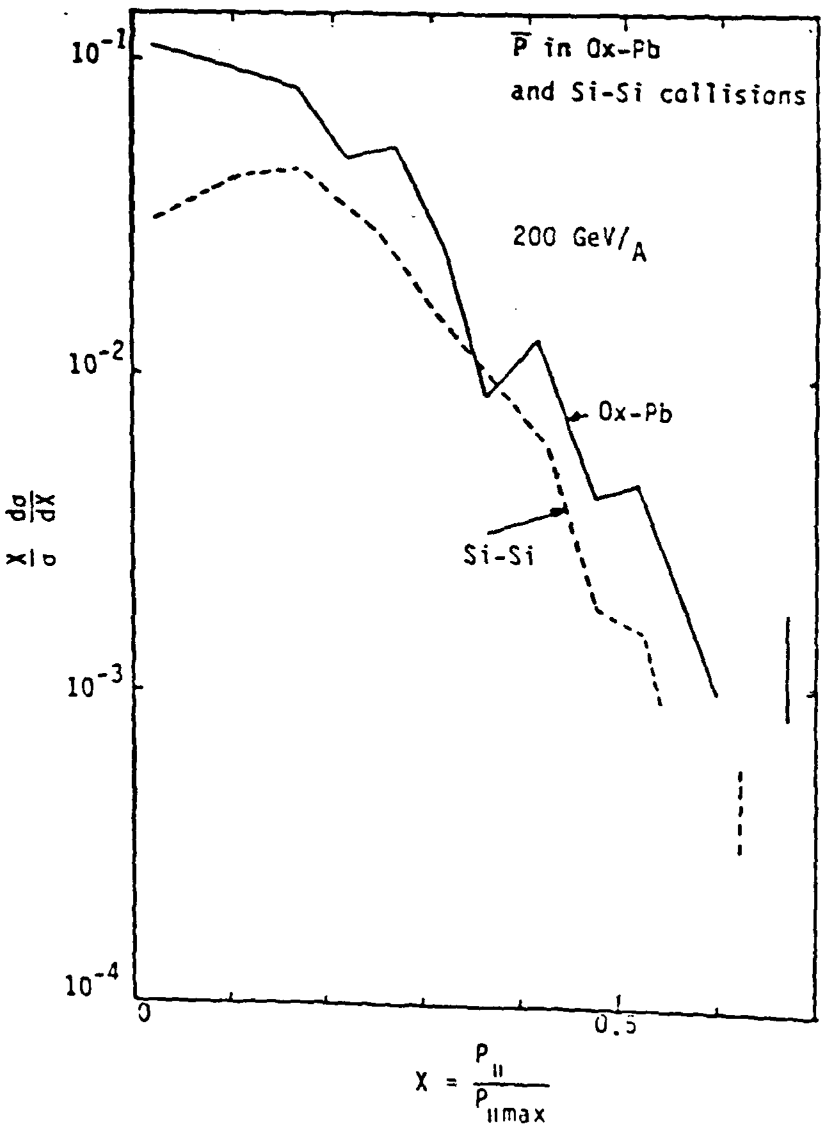
Si-Si collision
E_{lab}/A = 1000 GeV
10^0
10^{-1}
10^{-2}
10^{-3}
$\pi-\ x\ 10^{-2}$
$\pi+\ x\ 10^{-2}$
$\overline{P}$
$\overline{n}$
$\frac{x}{\sigma}\frac{d\sigma}{dx}$
0
0.5
$X = \frac{P_{\parallel}}{P_{\parallel max}}$

Figure 4.2



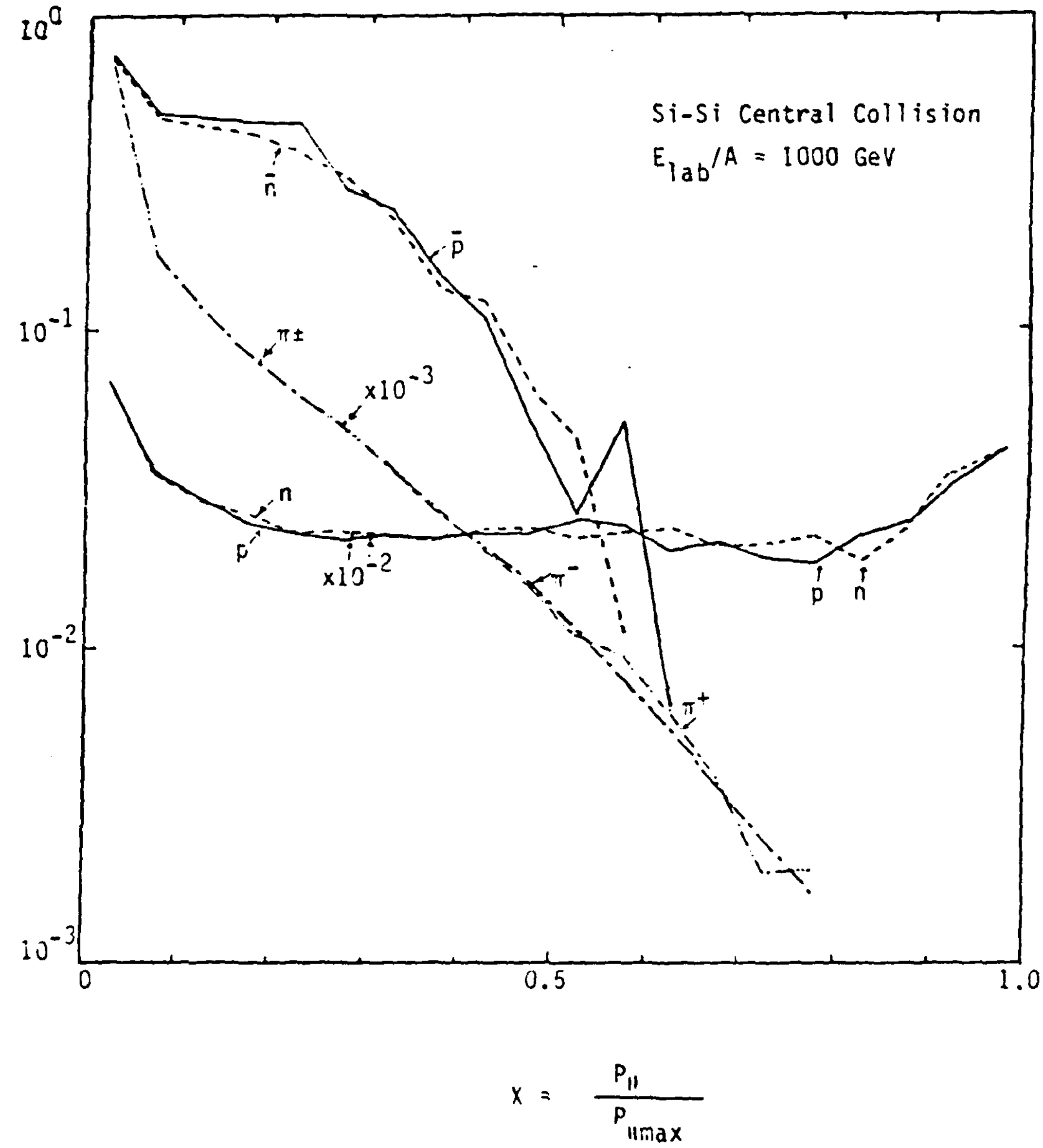
Cx-Pb collision
E_{lab}/A = 200 GeV
10^0
10^{-1}
10^{-2}
10^{-3}
$\frac{x}{\sigma}\frac{d\sigma}{dx}$
P x 10^{-1}
n x 10^{-1}
π^- x 10^{-2}
π^+ x 10^{-2}
$\bar{P}$
$\bar{n}$
0
0.5
1.0
$X = \frac{P_{\parallel}}{P_{\parallel max}}$

Figure 4.3



$\overline{P}$ in Ox-Pb
and Si-Si collisions
200 GeV/A
Ox-Pb
Si-Si
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\frac{x}{\sigma}\frac{d\sigma}{dx}$
0
0.5
$X = \frac{P_{\parallel}}{P_{\parallel max}}$

Figure 4.5



Si-Si Central Collision
E_{lab}/A = 1000 GeV
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
0.5
1.0
$\bar{n}$
$\bar{p}$
$\pi\pm$
$\times 10^{-3}$
n
p
$\times 10^{-2}$
π^-
π^+
p
n
$X = \frac{P_{\parallel}}{P_{\parallel max}}$

Figure 4.7

Central Collision

Xf spectrum concentrated to low Xf region

Recent Cern Experiment of Ox-Pb Collision

Pion Production 240 at 200 Gev Hydrodynamic
107 Venus Calculation
300 Venus Central

Sucsessive Collisions Increase P production

spectator Nucleus ~ 2 times of Proton collision

Multiple collision $\pi \rightarrow \bar{P}$.

Modification of Venus Code

- Important Sampling Method
- Russian Roulett,

Careful Choice of Parameter is required

Two Calculations of Collision Events

- Creation of the string
- The fragmentation of Strings
- Convolution of two functions

More Sophisticated model

- Flux Tube model
- Quark Gluon Plasma Formation

Dynamics of Plasma expansion and Hadronization
Heinz et al Theory

- Fragmentation model using string model.

- Baldin et al. C-Cu (3.8 GeV/A) $\bar{P}/\pi^-$ ratio 60 times of P-nucleus collision.